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Planning the Future of Smart Cities With Swarms of Fully Autonomous Unmanned Aerial Vehicles Using a Novel Framework

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ABSTRACT The autonomy of unmanned aerial vehicles (UAVs) - self-governing in the aerospace discipline has been a remarkable research area with the development of the advanced bespoke microcontrollers embedded with advanced AI techniques for the last several decades. The road forward about the operational environment is certain about the swarms of fully automated UAVs (FAUAVs), that is, urban areas. FAUAVs with self-learning and self-decision-making abilities by executing non-trivial sequences of events with decimetre-level accuracy based on a set of rules, control loops and constraints using dynamic flight plans and trajectories are taking their indispensable parts within smart cities (SCs). Therefore, their integration with the SC components using real-time data analytics is urgent. This is mainly required to establish a better swarm intelligence along with a safer and optimised harmonious smart ecosystem that enables cooperative FAUAV-SC automation systems with collaborative automated intelligence engaging in the concepts of Internet of Everything (IoE) and Automation of Everything (AoE). Planning the future of cities with swarms of FAUAVs is explored in this paper to optimise the use of FAUAVs with a diverse range of applications and a contemporary methodology is proposed using a holistic framework — FAUAVinSCF equipped with various effective and efficient techniques along with a novel FAUAV routing technique customisable to the constraints of FAUAVs and urban areas. With the methodology, the components of SC and FAUAVs involving recent and impending technological advancements are moulded together to make this inevitable transformation a harmonious part of the inhabitants contributing to the cities' liveability and sustainability. The framework consists of a decentralized agent-based control architecture that monitors and controls the swarms of resource-constraint FAUAVs for their real-time requirements in optimising their urban uses. The outcomes of the methodology suggest that the constraints of FAUAVs can be mitigated significantly in urban areas and consequently, their efficacy can be increased in realising their diverse range of missions.

INDEX TERMS Autonomous unmanned aerial vehicles (UAVs), smart city, Internet of Things (IoT), Internet-of-Drones (IoD), Internet of Everything (IoE), Automation of Everything (AoE).

I. INTRODUCTION

Evermore aspects of people's daily routines have been delegated to machines within the global emerging technological trend, and this trend looks set to continue in the future as the trust to intelligent machines increases [1] via increasing M2M autonomous intelligent communication links leading to swarm intelligence. Industry and government agencies envision the deployment of autonomous systems throughout society, especially autonomous vehicles that operate within urban infrastructures [2]. The exponential growth of the interest and investigations in unmanned aerial vehicles (UAVs) is strongly pushing the emergence of autonomous flying robots [3]. Most of the UAV manufacturers including Airbus are planning to deploy Level-5 fully autonomous UAVs (FAUAVs) soon. UAVs equipped with advanced miniaturised avionics, multiple sensors, actuators and onboard autonomous flight management control systems can be deployed economically with a high degree of rapid response time to accomplish many different types of urban tasks collaboratively with a high degree of mobility, such as logistics [4], remote sensing, search-and-rescue, medical supply delivery,

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humanitarian aid (e.g., in disaster-ridden areas such as flood, earthquake, hurricane), environment monitoring (e.g., power-line monitoring, agricultural surveying, forest fire monitoring, weather monitoring, chemical spills detection — e.g., providing real-time radiation levels of the damaged reactors at the Fukushima Daiichi nuclear power plant [5], traffic surveillance, crowd surveillance [6], borderline surveillance), photography/filming, inspection/maintenance, mapping, and law enforcement with their advantages over conventional vehicles regarding i) needing no physical road infrastructure with a direct, constant and high travel speed, ii) less exposure to traffic congestions, iii) ability to operate in dangerous and disaster-ridden environments, iv) ability to be deployed easily and rapidly, v) ability to cover a large terrain and vi) adjustable height to serve better and meet various requirements. On the other hand, in addition to the payload constraint, the capabilities of UAVs can be limited by the communication range between the operator at a remote base station (BS) and the vehicle and due to their limited battery capacity, UAVs need to return to BSs frequently for onboard battery recharging [7]. Moreover, most of the time, the data collected by onboard sensors can be acquired when they are back at their BSs because of the lack of real-time high-data-rate communication difficulties, which makes them impractical regarding acquiring and processing data in a timely manner. More importantly, the rapidly increasing number of UAVs operating in low-altitude urban airspace poses a security challenge with the imminent traffic chaos that needs to be addressed urgently even though various UAV traffic management systems (UTM) are established by several countries to ensure the safe use of UAVs with the near-real-time UAV monitoring and management services.[1]

It is unrealistic to consider smart cities (SCs) without UAV services. Successful implementation of more complex urban tasks by UAVs comes with the improvement of their capability in autonomy with the coordinated real-time applications in a cooperative and collaborative ecosystem by alleviating their constrains with emerging advanced technologies. Therefore, it is highly imperative to make UAVs fully autonomous supported by SC optimally geo-distributed facilities by which they can be more functional and safer. Autonomy is defined as the ability of a system to sense, communicate, plan, make decisions and act without human intervention [9]. There have been many research studies on UAVs reporting progress towards autonomic systems that do not require direct human interventions [10]. FAUAVs equipped with advanced technologies and engaging with the SC components can accomplish various tasks with no intervention in the urban areas safely, in particular, with no needing the supervision of drone pilots with their increased capabilities — flight range: 150 km [11], payloads: 1000kg [12], missions under any adverse weather circumstances.

[1]Interested readers are referred to the study [8] for the most recent regulations and policies for the use of UAVs in the urban areas.

The use of different types of fully autonomous vehicles (e.g., autonomous underwater vehicles, autonomous ground vehicles (AGVs) [13]) have been analysed in various studies, and it is worth emphasising that only FAUAVs are focused in this study. To the best of the observed knowledge, this is the first study that highlights a research gap in the field of the integration of FAUAVs with SC, which leads us to analyse this integration from a scientific and philosophical point of view. Forging the abilities of FAUAVs with a high degree of autonomy and abilities of SC with a high degree of collaborative intelligence paves the way for the development of more synergistic ecosystems accommodating both a high level of efficient mobility for FAUAVs and a high level of sustainability for cities. To clarify the novelty of this paper, particular contributions are outlined as follows.

1) The main components of FAUAVs and their necessary integration requirements with SC domains involving recent and impending technological advancements are analysed to increase the efficacy of FAUAVs within SC where both FAUAVs and SCs can evolve within a new cooperative and collaborative ecosystem. Within this context, a synergistic holistic framework — FAUAVinSCF is proposed to make FAUAVs cooperate more efficiently with one another within their complex ecosystem using mission-oriented swarm intelligence.
2) FAUAVinSCF aiming at alleviating the main constraints of FAUAVs and contributing to the cities' liveability and sustainability with a new way of thinking is designed to increase the efficacy of ubiquitous battery-constraint, coverage-constraint and resource-constraint systems within SC.

The remainder of this paper is organised as follows. The related works with the review of early concepts are explored in Section II. The methodology along with the proposed framework is explored in Section III. Results and discussion along with open issues and virtues of the proposed framework are provided in Section IV. Finally, Section V draws conclusions and unveils directions for potential future ideas.

II. RELATED WORKS

The advances in communication, computation, and sensing technologies have led researchers, academics, and aircraft industries to strive to design efficient enabling technologies for UAVs [14]. As autonomous capability and reliability increase, the prevalence of autonomous vehicles in people's daily socio-technological lives becomes inevitable [2]. Most of the UAV manufacturers plan to deploy FAUAVs soon for specific types of tasks by leveraging extensive existing knowledge about sensors, actuators, telematics, microcontrollers, electro-mechanical systems, avionics, onboard autonomous flight management control systems, cyber-physical systems (CPSs), mobile edge computing (MEC) and AI approaches gained from the previous lower level of autonomy attempts. There are many attempts to improve the capabilities of UAVs mainly in i) increasing battery and payload capacity, and processing power with advanced miniaturised avionics, and ii) using clusters of them with swarm intelligence to accomplish various collaborative tasks with collective behaviour. Compared with a single platform, cooperative autonomous UAVs offer efficiency and robustness in performing complex tasks [15]. Since 2000, the realm of autonomy for unmanned systems has been advancing rapidly, as algorithms that assist unmanned platforms to independently execute roles and behaviours without instruction from the outside have matured [16]. Since 2012, extensive research has been conducted about the design and urban use of FAUAVs [17]. Autonomous control can be defined as a higher level of automatic control in a very unstructured environment providing a level of autonomy that can detect and respond to anticipated events and conditions [18]. Within this perspective, the autonomy of UAVs — self-governing in the aerospace discipline has been a remarkable research area with the development of the advanced bespoke microcontrollers embedded with advanced AI techniques for the last several decades. 10 control levels of UAV swarms from fully supervisor-controlled to fully autonomous mode between human and machine were analysed in [19]. Recently, Drone Industry Insights (DRONEII) categorises the autonomy with 5 levels [20] based on degrees of independence, namely, 1: low automation (i.e., the UAV has control of at least one vital function, a pilot in control); 2: partial automation (i.e., the UAV can take over heading, altitude under certain conditions and a pilot still responsible for safe operation); 3: conditional automation (i.e., the UAV can perform all functions and a pilot act as a fall-back system); 4: high automation (i.e., the UAV has back-up systems, so if one fails, the platform is still operational and a pilot is out of the loop); 5: full automation (i.e, the UAV can plan its actions using advanced AI autonomous learning techniques) with little or no human in the loop. As the level of autonomy increases, UAVs can operate in more complex environments and execute more complex tasks with less prior knowledge and fewer operator interactions [21]. Additionally, with swarm intelligence, various tasks can be completed collaboratively using an array of FAUAVs. Usually, bio-inspired approaches (e.g., bee/ant colony) are followed to establish swarm intelligence in a system composed of a large number of intelligent agents. In this regard, recently, an autonomous learning approach, ''self-organizing maps (SOMs)'' which can automatically and adaptively coordinate a large array of autonomous drones is proposed in [22]. An effective swarm intelligence with FAUAVs requires high-quality communication enabling real-time transferring of big data (BD), and long flight durations.

It is expected that 5G (fifth-generation) wireless mobile communication will provide the means to allow an all-connected world of humans and devices which would lead to a global low-powered wide-area network (LPWAN) solution for Internet of Things (IoT) applications [23]. Thanks to the continuous improvement in the UAV payload weight and communication device miniaturisation, it becomes more feasible for UAVs to carry various types of communication equipment in the sky, to provide or enhance the communication services, so-called UAV-assisted air-to-ground (A2G) terrestrial wireless communication for the ground users in the cellular networks [24] and ground nodes (e.g., IoT, a large number of sensor nodes with long lifespans) in LPWAN or wireless sensor networks (WSN) (i.e., UAV-assisted WSN) in addition to enabling cellular-connected air-to-air (A2A) UAV communication. The use of the LTE (Long Term Evolution) cellular networks on UAVs has been performed successfully with promising results [25]–[27]. Achieving high-speed 5G wireless communication has emerged as one of the applications of UAVs [14]. China Mobile and Sweden's Ericsson teamed up to conduct what they say is the world's first 5G-enabled drone prototype field trial to improve latency for mission-critical use cases [28]. Several leading companies such as Facebook with Aquila and Google with Titan projects initiated drone-based Internet services with highly minimised human supervision to establish an effective A2G communication link that could deliver data at tens of gigabits per second using laser beams [29]. The laser communication with Aquila project could deliver high-speed internet to BSs on the ground, connecting everyone within 50 km [29]. Google's project, SkyBender delivers Internet at speeds 40 times faster than 4G (fourth-generation) systems in the Mexico desert using UAVs equipped with 5G technologies [30]. The significantly improved capabilities of 5G networks will provide more efficient and effective mobile connectivity for large-scale drone deployments with more diverse applications [31].

When UAVs do not use any alternative energy sources from the ambient environment, they may fail to several tasks due to the limited operating time and the sustainable sources of power are considered as an effective solution [32]. Several studies [33]–[35] propose multiple charging stations distributed optimally in urban areas to allow UAVs to recharge their batteries when needed. A solar-powered drone in the sky was able to fly for two weeks as a world record [29]. If the aircraft can achieve continuous flight without refuelling or recharging by ground support, the aircraft can partly carry out a mission as an artificial satellite [36]. In this regard, the first UAV of its kind to fly in the stratosphere, Zephyr harnesses the sun's rays, running exclusively on solar power, above the weather and conventional air traffic. It is a high-altitude platform (HAP): a high altitude pseudo-satellite, able to fly for months at a time, combining the persistence of a satellite with the flexibility of a UAV.[2] If Facebook could build a drone that gathered most of its power from the Sun, Zuckerberg reasoned, it could fly for 90 days. The constraint of frequent charging requirement of UAVs can be substantially alleviated with solar energy, which will speed up the use of similar UAV technologies all around the world. However, there is a non-trivial trade-off between harvesting more solar energy at higher altitudes over clouds and improving communication performance since higher flight altitudes lead to a more severe

[2]https://www.airbus.com/defence/uav/zephyr.html

path loss for A2G communications [37]. More importantly, many tasks carried out by FAUAVs such as environmental monitoring, delivery requiring low altitude motion are based on low-altitude platforms (LAPs). In this case, this constraint can be alleviated using wireless power transfer (WPT) as a very good candidate with higher flexibility and lower maintenance costs, which is elaborated in the following paragraph.

Dedicated wireless energy transmission using electromagnetic power transfer, optical power technology (e.g., laser beams) has massively been investigated with promising outcomes [38]–[43], which may remove the battery life constraint of UAVs soon. These WPT approaches permit a very efficient and reliable power transmission between the ground base and the UAV [44]. Within this context, wireless ground charging stations (WGChS) for recharging UAV batteries using wireless powered UAVs that can be charged by energy carried by radio signal (especially for the microwave that travels hundreds of meters) is proposed by Yin *et al.* [33]. Severe propagation losses during wireless energy transmission can be compensated by short distance Line-of-Sight (LoS) energy transmission links [45]. Depending on the antenna size, transmitting power and the propagation environment, and radiative (i.e., electromagnetic) frequency, WPT using concurrent omnidirectional power delivery to multiple receivers requiring smaller transmitter/receiver may achieve power delivery over distances varying from a few meters to even hundreds of kilometres. These features make aforementioned WPT approaches suitable for the use of UAV environment compared to the near-field inductive coupling WPT with a range of up to several centimetres and magnetic resonant (MR) WPT with a range up to several meters where the transmitter and receiver need to be in close proximity [43], [46], [47]. More explicitly, radio frequency (RF) transmission enabled WPT is a promising solution to provide perpetual and cost-effective energy supplies to low-power electronic devices, and it is anticipated to have abundant applications spanning from low-power wireless charging for devices such as radio frequency identification (RFID) tags, wireless sensors, IoT, and consumer electronics (smartphones, laptops, household robots, etc.) to high-power applications such as microwave-powered aircraft [43], [48]. It is worth mentioning that even though the laser-based WPT approach can provide perpetual power supply to UAVs in flight with a range up to several kilometres using LoS link, its limitations such as being vulnerable to atmospheric absorption and scattering by clouds, fog, and rain, hinders its practical applications [43]. Another issue with the laser beam transmitter is that it can only power a single UAV at a time [49]. Against these drawbacks, the company Lasermotive has demonstrated a working prototype of a UAV that can remain in the air indefinitely using a kilowatt laser that transmits a beam of energy at a specially designed photovoltaic panel on the UAV [49], [50].

The amalgamation of UAVs with IoT, advanced sensor technologies, and cloud/edge computing has extended their role in the design and development of future SCs [14] with various use cases [51]. FAUAVs as flying autonomous robots determining their course of actions with onboard sensor data analysis involving autonomous take-off and landing are taking their places in real-life to accomplish many different tasks. Airbus has recently tested autonomous unmanned aerial systems (UASs) successfully.[3] The use of FAUAVs in the autonomous health monitoring of civil urban structures (e.g., electricity lines, wind turbines) is widespread. Autonomous deliveries using UAVs have launched in some cities, and it won't be long before UAV drop-offs will be a regular occurrence [52]. The autonomous UAVs, namely DJI Phantom IV Pro (using the Intel Movidius Myriad 2 vision processing unit) and Skydio R1 (built around the more powerful NVIDIA Tegra X1 system-on-a-chip) are being deployed for autonomous videography/filming purposes [53]. An autonomous fixed-wing UAV, so-called, Zipline that can be classified as Level-4 task-level autonomy has been saving lives in Rwanda and Tanzania by delivering critical medical supplies at night, through heavy rain, or in high winds from a central distribution centre to hospitals across the country in minutes within 75 km with a mission-level autonomy where the other transportation modes seem to be far from feasible with bad road infrastructures along with the adverse weather conditions [11]. Zipline fired into the air with a catapult using GPS navigation in coordination with the country's air traffic control heads for its target, operates standalone through predefined waypoint routes, informs the responsible people with a message upon its arrival via an air-to-user (A2U) communication link, drops the package in a padded container with its little parachute, heads back home for an arresting-hook-assisted landing onto a soft mat, and finally gets ready to fly again after a quick battery swap.

While FAUAVs as an efficient mode of fulfilling various tasks with the abilities of self-configure, self-operate and self-heal are taking their places in city aerial routes, today, and every day, worldwide, one million more people are born-into or move-into a city, and it is envisioned that this will continue for the next 30 years [54]. The global population is expected to double by 2050 [55] and more than 68% of the population will be living in an urban environment by 2050, most visibly in developing countries [56] with a population of 5 billion [57]. Due to the ever-growing demands of citizens, economic concerns, and imminent environmental risks, the pressure is growing on city governments to leverage every opportunity to improve the quality of life for inhabitants [58] with highly increased quality of services. In this manner, to alleviate the problems of rapid urbanisation and to improve the liveability of citizens, there are many concerns to be taken into account in urban development and management [59]. On one hand, it was shown by the recent studies that the dominant reason for the 150 reported UAV crashes is the loss of UAV-ground communication [24], which further affirms the limitation of the current approaches to control UAVs.

[3] https://www.airbus.com/innovation/autonomous-and-connected/unmanned-aerial-systems.html

As the number of FAUAVs and the demand for new types of FAUAV applications is expected to increase explosively shortly, it is of vital importance to devise innovative solutions to support high-performance communications between UAVs and the ground [24]. On the other hand, the lack of appropriate real-time decision-making strategies is the cause of many accidents involving UAVs according to the reports presented by the US Federal Aviation Administration [60]. In this regard, an onboard real-time decision-making approach for a single FAUAV is designed and tested in [60]. To deploy FAUAVs in urban airways effectively and safely, city governors do not seem to be empty-handed, full of ammunition, on the contrary, makes them exploit this forthcoming technology substantially — turning the challenges into advantageous tools. Recent advances in cyber-physical domains, cyber-physical-social systems, cloud, cloudlet, and edge/fog platforms along with the evolving BD analytics, Internet of Everything (IoE), Automation of Everything (AoE) [61], Advanced Insight Analytics (AIA) [61], 5G-based IoT-enabled Internet-of-Drones (IoD) [62], ubiquitous sensing, location-independent real-time monitoring and control, dynamic vision analysis, heterogeneous network infrastructure, and cutting-edge wireless communication technologies (e.g., 5G and beyond (5GB)) are providing many opportunities and urging city governors to pursue the ways that enable intelligent management of cities [59]. In this sense, to reduce the burden on cities and to make them smarter and sustainable, a novel framework entitled "TCitySmartF" was proposed in a recent study [59] that demonstrates a variety of insights and orchestrational directions for local governors and private sector about how to transform cities into automated and connected smarter cities from the technological, social, economic and environmental point of view, particularly by putting residents and urban dynamics at the forefront of the development with participatory planning for the robust community- and citizen-tailored services. Nonetheless, the literature analysis has shown that there is no comprehensive study, in particular, attempting to integrate FAUAVs with SC ecosystem. This paper highlighting this significant research gap and proposing a holistic framework — FAUAVinSCF moulds the components of SC and FAUAVs in an orchestrated and synergistic way leading to the functional improvement of FAUAVs along with urban resource-constraint devices and optimisation of urban mobility, particularly, urban aerial traffic flow. More particular previous studies related to the particular approaches and techniques within the proposed framework are elaborated while the framework is being explored in Section III.

III. METHODOLOGY

Before revealing the proposed techniques and approaches in Section III-B, the main features and components of FAUAVs and SCs are explored briefly in Section III-A to make these techniques and approaches easier to understand with the agreed-upon terminology.

A. BACKGROUND OF THE METHODOLOGY

SCs and FAUAVs have their particular components and these components need to be well integrated harmoniously to result in a synergistic environment benefiting both FAUAVs and SC objectives. These components summarised in Fig. 1 which are the basis for integrating FAUAVs with SC are scrutinised in the following two subsections to shed light on an effective way of smoother integration.

1) MAIN FEATURES AND COMPONENTS OF FAUAVs

Different from the ground-based autonomous driverless vehicles, FAUAVs have diverse characteristics and they are designed with particular features and onboard equipment concerning the missions they are expected to perform. Compared with rotatory-wing FAUAVs, fixed-wing FAUAVs can carry more payload that allows carrying more fuel or battery capacity where wings cause air passing underneath with less thrust from the motors leading to natural aerodynamic lift and requiring less energy consumption during navigation and hence, fixed-wing FAUAVs generally have a longer range and can complete missions requiring longer flight durations. However, fixed-wing design requiring large areas for take-off and landing along with steady forward movement is not suitable to the urban use for many types of operations, which makes rotary-wing more appropriate for urban use with a cost of more energy consumption because of the excessive thrust from the motors to stay in the air.

Different networking hardware, protocols, and sensors can be combined to create diverse and complex UASs through a layered design approach with modular software [63]. The development of low-cost micro-electro-mechanical systems and powerful microcontrollers help the use of UAVs as autonomous within longer ranges where more payloads lead to less battery life. In plain terms, FAUAVs are equipped with various miniaturised avionic capabilities, high onboard processing power with low-power embedded processors, long-battery-life, up-to-date HD maps, sensors, advanced AI tools, and actuators to safely interact with the environment, BSs and other vehicles using advanced communication technologies. Hence, they avoid any accident and perform their tasks successfully with no or less human intervention. They can first, i) sense the environment, second, ii) interpret and plan proper actions in regards with the main objectives and finally, iii) act appropriately using the robust combination of network, hardware, and software components. Those components are presented in Fig. 1 D and E.

Sensing and actuation in FAUAVs: Visual perception of the current state of their surroundings is performed by FAUAVs using a variety of sensor technology known as LOS sensors to perform their mission-critical tasks. More precisely, FAUAVs equipped with cameras with different characteristics, lidar, radar, proximity sensors, inertial measurement unit (IMU) and inertial navigation systems (INS) observe their environment and collect required data to complete their tasks by following appropriate manoeuvrers.

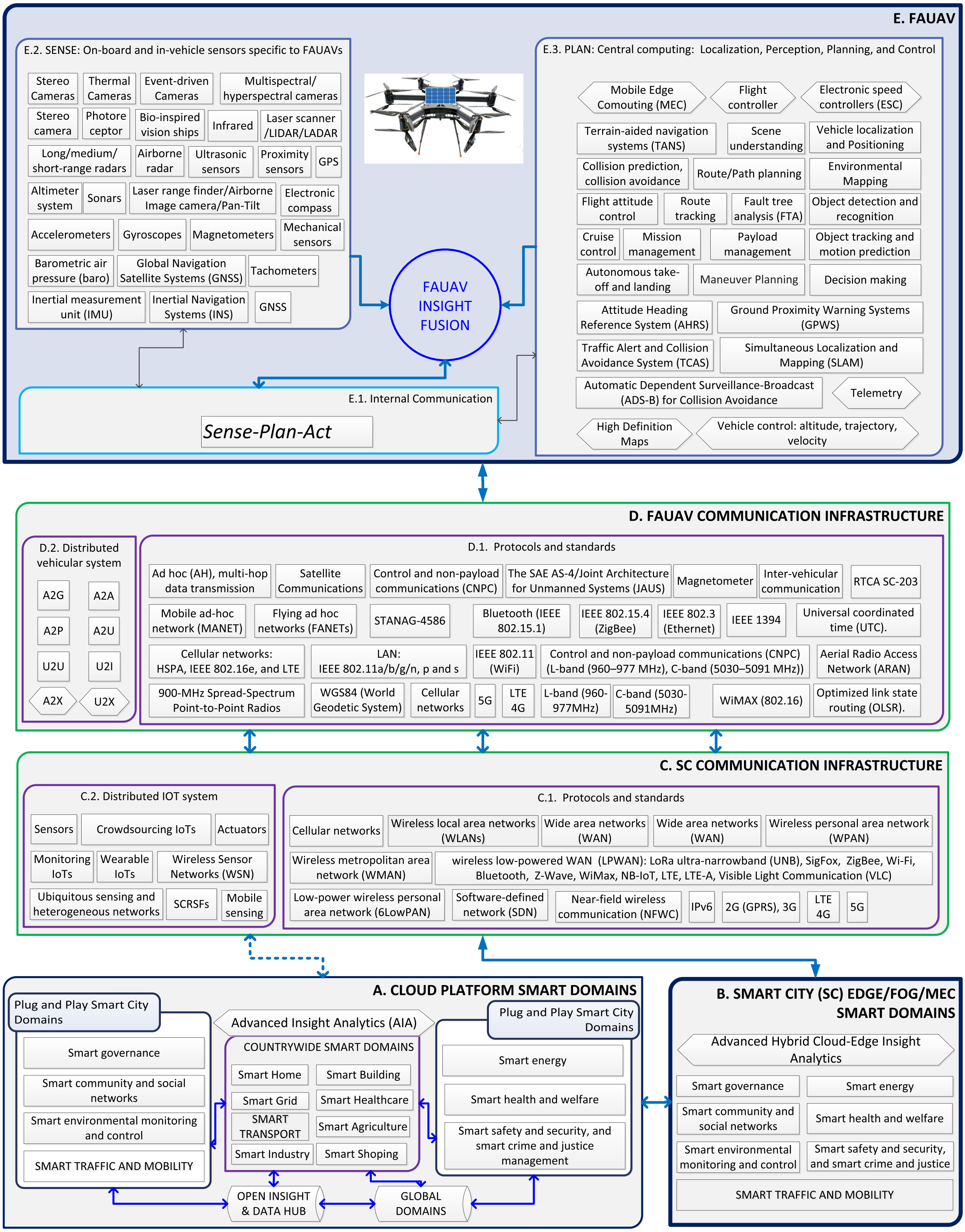

FIGURE 1. **Main components of SC and FAUAVs and their integration with one another using their current communication abilities.**

The main onboard sensor and actuation mechanisms on FAUAVs are displayed in Fig. 1 E2. Interested readers are referred to the study [64] for more detailed information about these sensor technologies, how they function and how data acquired from different combinations of them is fused for decision-making.

FAUAV subsystems, communication and cooperation: The onboard processing ability of sensor data and the decision-making ability of FAUAVs with the help of the onboard mobile edge computing (MEC) platform not only make them increasingly autonomous, but also, communication link failures and high bandwidth data communication requirements with processed and reduced data are alleviated. The main sub-systems using AIA are presented in Fig. 1 E.3.

UAV communication is an emerging and underexplored field [26]. The communication protocols and standards used in UAVs are shown in Fig. 1 D. FAUAVs establish A2G, A2A, and A2U communication links to perform their missions as desired. Leveraging publicly available cellular networks are useful to provide wide-area A2G coverage without additional infrastructure while Wi-Fi technology with the IEEE 802.11 protocol can be used for the A2A links [65] that allows high-bandwidth connections for sending and receiving large amounts of data over the links [63]. Integrating UAVs into the cellular network is envisioned to be a promising technology to significantly enhance the communication performance of both UAVs and existing terrestrial users [24]. Current 4G LTE systems are used to increase network expandability up to hundreds of thousands of connections for low-cost, long-range, and low-power machine type communication (MTC) and IoT devices [6]. The recently developed advanced communication system, 5G supporting three-dimensional (3D) connectivity—namely a characteristic referring to the ultra-high reliability, ultra-high availability, and ultra-low latency features of UAVs will be the communication standard to support the long-distance, high altitude, and high mobility nature of UAVs [6] with a very high data speed (i.e. exceeding 10 Gb/s) and extremely low latency (i.e., 1 ms) even though 5G with high-frequency millimetre-wave technology provides shorter communication range in comparison to the traditional wireless communication technologies [66]. Furthermore, it was shown that leveraging multiple UAVs using 5G technology not only provides long-range connectivity but also better load balancing and traffic offload leading to a significant capacity enhancement [67].

The current cellular system is designed to support a limited number of connections with high-rate downlink data traffic [68]. On the other hand, satellite communication with very low bandwidth is employed for long-range missions. FAUAVs as mobile communication nodes can receive the required information and send the collected data at pre-specified locations within the communication range to mitigate the aforementioned communication bottlenecks. Alternatively, FAUAVs can carry out their tasks using communication with ground control stations (GCSs) and other UAVs using two data transmission modes where no effective communication network channel is established between GCSs and UAVs, namely, ad hoc (AH) mode and store-carry-and-forward (SCF) mode [69]. In AH mode, data is transmitted to BSs by multi-hop transmission acting as relays. For flying AH networks (FANET) using broadband AH network technology for connecting UAVs, the system cannot predict and effectively control the node to move regularly in a complex environment due to the inherent randomness of both the transmission environment and the mobility of UAVs [70]. Although FANET has been widely investigated to mitigate the communication drawbacks among many UAVs, these works cannot answer the questions in FANET based on high mobility and limited energy [71]. On the other hand, in SCF mode, data is first forwarded to the returning UAV — e.g., for charging the battery and the data is brought to GCS by the returning UAV.

UAV HAP-based communications (17 km and above the earth's surface) have several advantages over the LAP-based communications (a few kilometres above the earth's surface), such as wider coverage and longer endurance [72]. Thus, HAPs are in general preferred for providing reliable wireless coverage for very large geographic areas. On the other hand, compared to HAP-based communications, or those based on terrestrial or satellite systems, wireless communications with low-altitude UAVs (typically at an altitude not exceeding several km) also have several important advantages [72]. UAVs using UAV-supported ultra-dense networks with ultra-high data rate and very low time delay can be rapidly deployed to serve wireless users without being hampered by geographical constraints compared to conventional terrestrial infrastructure with fixed locations [71]. LAPs have recently gained significant popularity as key enablers for rapidly deployable relief networks where coverage is provided by onboard radio heads and they are capable of delivering essential wireless communication, in particular, for public safety agencies in remote areas or during the aftermath of natural disasters [73]. Interested readers are referred to the studies [63], [74], and [72] for more detailed information about the UAS communication.

2) MAIN FEATURES AND COMPONENTS OF SC

A holistic SC framework is presented in [59] and the main objectives of establishing SCs are summarised as i) enabling the integration of the distributed services and resources in a combined synergistic fashion, ii) improving existing public services and providing new effective citizen-centric, user-driven, and demand-oriented services, iii) monitoring a city with easy-to-use visualisation tools, iv) enabling near-real-time services for end-users and/or further smart actuation, v) increasing the sustainability with optimised services, and vi) driving economic development, innovation, and global city investment competitiveness. The cloud platform (placed in the dedicated section titled "A. Cloud platform smart domains" in Fig. 1) with vertically expandable data storage and processing capabilities has the advantages for massive storage, heavy-duty computation, global coordination and wide-area connectivity [75], while edge, fog and MEC (placed in the dedicated section titled "B. Smart City (SC) edge/fog/MEC smart domains" in Fig. 1) are useful for real-time operations and responses, rapid innovation, user-centric services, and edge resource pooling [76].

Strictly speaking, cloudlet, edge, fog and most recent popular platform, so-called MEC are the emergent architectures for computing, storage, control, and networking that distributes these services closer to end-users [76] to enable a more independent processing and organisation, particularly for the applications requiring real-time decision-making, low-latency, ultra-low-latency, high privacy and security with mobile services [59]. To enable low-latency and increase efficiency further, multiple edge/fog/MEC nodes may be needed to support highly distributed devices and systems over large geographic areas [59]. Data collected either from IoT devices or users is aggregated, sanitised, filtered, processed for insight generation and compressed in the fog platforms to be sent to the cloud resulting in reduced network traffic, computation and storage costs in the cloud platform [59].

Sensing, actuation and communication in SC: The large deployment of sensor nodes in WSN, IoT and advanced mechatronic systems (AMS) is actually enabling SC initiatives all over the world using the sensing and actuating capabilities of everyday objects [77], [78]. With IoT and AMS, physical objects equipped with microcontrollers, transceivers for digital communications, and suitable protocol stacks are seamlessly integrated globally so that the physical objects can interact with each other and to cyber-agents to achieve mission-critical objectives [79], [80]. IoT ecosystems play a vital role to gather rich sources of information and different cities have already deployed IoT infrastructures and a variety of sensory devices to collect continuous data [81]. By offering lower cost, lower energy consumption and support for a very large number of devices, 5G is ready to enable the vision of a truly global IoT [82]. WSN with various dense or sparse sensor nodes equipped with energy harvesting (EH) mechanisms, enabling the collection of environmental data from a countless number of widespread sensor nodes is the main building block in establishing effective SC applications with insights fused from BD collected from city environment using advanced data analytics (e.g., water level or speed of a river, pollution or noise level, forest fire detection) [61]. Most recent data analytic tools designed to work on the cloud platform are analysed in [83]. The orchestration of resources and network traffic across geo-distributed nodes are provided using specialised interfaces such as OpenStack and OpenFlow enabling software-defined network (SDN) controller to manage distributed nodes effectively. The evolution of SDN allows for a logically centralized but physically distributed control plane by eliminating vendor dependency and compatibility issues between different networking devices [84].

The connectivity of the SC objects relies on different types of networks and communication technologies to perform collaborative tasks for making the lives of the inhabitants more comfortable [85] in seamless communication ecosystem as shown in the dedicated section titled "C. SC Communication infrastructure" in Fig. 1. Heterogeneous networks integrating cellular networks, wireless local area networks (WLANs), wide-area networks (WAN), wireless personal area network (WPAN), wireless metropolitan area network (WMAN) are the backbone of SC and aim to provide a wide variety of connectivity services with seamless communication between the physical and cyber world in a highly interconnected smart public infrastructures and services [59]. Solutions based on cellular communications (e.g., 2G, 3G, and 4G) can provide larger coverage, but they consume excessive device energy; therefore, IoT applications' requirements have driven the emergence of new wireless communication technology — LPWAN because of its low power, highly energy-efficient (i.e. 10+ years of battery lifetime [86]), long-range with a robust signal propagation (i.e., up to 10 km in urban areas [23]) and low-cost communication and operation (i.e., \$1 per device per year [87]). LPWAN represents a novel communication paradigm, which will complement traditional cellular and short-range wireless technologies in addressing diverse requirements of IoT applications within SC [87]. LPWAN with a star topology and long-range radio links supplying wide-area coverage has the potential to complement current IoT standards as an enabler of SC applications whereas multihop routing in mesh topology generally yields long communication delays, and unequal and unpredictable energy consumption among the devices [88]. IoT anywhere and anytime devices spanning several kilometres are integrated using IPv6 addressing, particularly via low-power wireless personal area network — 6LowPAN. Several wireless LPWAN technologies enabling a wide coverage and low-power solutions such as LoRa ultra-narrowband with an urban range of 2-5 km, SigFox with an urban range of 3-10 km, NB-IoT with an urban range of 1 km [23], Ingenu with an urban range of 15 km and Telensa with a range of 1 km [87] enable the ubiquitous network connections for offering large-range coverage and deployments of power-constrained wireless IoT nodes and sensor nodes [23], [77], [89] along with 3G/4G, millimetre-wave communications, Zig-Bee (10-20 m, 250 kb/s), Wi-Fi (100 m) or Bluetooth (1-100 m, 1–2 Mb/s), Z-Wave (100 m), WiMax (50 km), LTE (30 km), LTEA (30 km) using small cell technology and Visible Light Communication (VLC). Throughout these technologies, public Wi-Fi primarily supports the real-time SC applications in a crowdsourcing way, particularly, using location-aware services [59]. The use of 5G with high capacity, high speed, high data transmission rates, high reliability, high availability, high throughput and low-latency abilities will increase the efficacy of communication not only between the SC components and CPS platforms, but also, between FAUAVs and SCs.

SC Domains: The main smart domains within SC are smart government, smart environmental monitoring and control, smart energy, smart community and social networks, smart safety, security, crime and justice, and smart traffic and mobility.[4] These domains are not only strictly connected to each other, but also with the countrywide and global smart domains in the cloud platform to create a harmonious

[4]Interested readers are referred to the study [59] for detailed information about these SC domains.

synergistic city environment coordinated globally as shown in the dedicated sections titled ''B. SC edge/fog/MEC smart domains'' and 'A. Cloud platform smart domains'' in Fig. 1. Management of FAUAVs in SC essentially should be integrated with the SC domain, ''smart traffic and mobility''.

The main goal of smart traffic and mobility is to monitor city dynamics and direct these dynamics to make a city life smoother and easier (e.g., optimal mobility, less congested, less polluted environment) [59]. The intelligent mobility and traffic system could enable us to calculate the best route in real-time by connecting different transport modes to save time and reduce carbon emissions [77]. The essential elements of this domain are i) smart traffic management (e.g. traffic monitoring, routing, prediction and directions, smart traffic signals/lights), ii) smart public transportation with public transport networks involving a shared ride (e.g., shared taxis, flexible car-sharing), iii) smart cycling (e.g., shared bikes), iv) intelligent parking, v) intelligent delivery (e.g., package delivery, fresh food delivery by trucks and autonomous vehicles), vi) smart human mobility and commuting (e.g., elder, disabled people mobility) and pedestrian management (e.g., the flow of people), vii) smart autonomous driving supported by new hybrid and electric vehicles, and AGVs, viii) collision avoidance, ix) autonomous toll collection, and x) smart supply chain integrated with ''smart industry'' and ''smart shopping'' [77]. All these elements involving FAUAVs should be orchestrated properly and appropriately to generate smooth mobility and aerial traffic within SC.

B. INTEGRATION OF FAUAVs WITH SC

The concepts of IoE and AoE bring the people, organisations, lives, processes, data, and things into a concrete coherent structure - CPSs to develop a synergistic smarter connected globe with diverse applications [59]. Strictly speaking, the global emerging technological concept is on the verge of integrating everything on a location-independent basis within the concept of AoE with the help of CPSs connected to the SC edge/fog/MEC platforms and cloud platform. With this in mind, most of the current SC development and enhancement attempts are mainly focusing on urban mobility and a huge amount of investment has been underway in sensor-rich mobile devices, particularly in autonomous vehicles to support crowdsourcing applications to be able to observe the instant urban dynamics for near-real-time smarter decision-making [59]. Cellular network capacity can reach near-limits because of heavy traffic coming from cellular networks [90]. UAVs may potentially overcome the communication challenges of IoE by providing effective communication coverage links between resource constraint IoT devices [91]. An SC framework is presented in [59] and FAUAVs within SC cannot be independent and should be incorporated well into the SC framework both to realise their objectives swiftly and to be more functional with the other components of SC enabling smoothly working SC ecosystem. FAUAVs with the promising abilities of i) charging/fuelling and controlling itself with the power of being electrical, ii) sensing its environment using its sensors, and iii) collecting BD via sensors and M2M communication to complete their mission by adopting the environmental dynamics are expected to impact the SC mobility and countrywide and international smart transportation/logistics substantially by alleviating the problems of urbanisation. For instance, 86% of parcel delivered by Amazon weigh below 5 pounds (<2.5 kg) [92] and the average weight of parcels delivered by FedEx is less than 10 pound (<5kg) [93] and it can be safely concluded that a great majority of parcels can be delivered via airways using current UASs, which help ease the logistics in urban areas substantially.

Despite various advantages over conventional ground vehicles, FAUAVs have operational constraints with the communication drawbacks, flight range limit with the limited onboard energy, and payload capacity that reduces the onboard computation power, storage space and communication abilities along with the quality and the number of sensors significantly. These constraints can be mitigated within SCs with the objectives of creating sustainable and safe cities by minimising the number of vehicles in the aerial traffic and vehicle-miles travelled (VMT) with optimised routing, but increasing the work done by UAVs. UAVs are expected to be an important component of 5G/5G and beyond (5GB) cellular architectures that can potentially facilitate wireless broadcast or point-to-multipoint transmissions [94]. In this regard, an advanced UAV-based 5G network that aims to cover the communication ranges of all UAVs over the city is incorporated into this study. The 4G LTE and 5G/5GB communication technologies enable FAUAVs with the computing and storage resource restrictions to offload intensive computations to the SC edge or other MEC platforms such as the lead FAUAVs with advanced abilities. The edge-based UAV swarm, which brings computing resources to the edge of the network, is considered as a promising solution to improve the high latency and low energy efficiency [95]. Within this context, the leader FAUAVs (LFAUAVs) embedded with intelligence data analytics capabilities are the key enablers for establishing the SC aerial LFAUAV MEC platform in the proposed framework to connect SC and all other FAUAVs smoothly. The general features of LFAUAVs are presented in Fig 2. They charge themselves using the solar energy, WGChS or they can be charged in the air using advanced charging approaches supported by SC. How these advanced features of LFAUAVs are employed in incorporating FAUAVs into SC is explored in the following subsections in detail. It is worth noting that every FAUAV should have on-board processing and decision-making abilities at least to take a safe action where the communication link with LFAUAVs or SC is lost.

The SC LFAUAV MEC platform as an integral part of SC is composed of optimally distributed LFAUAVs. FAUAVs can collect very big data volumes during their missions within SC. Allocation of limited resources, in particular, on the SC LFAUAV MEC platform should be carefully designed regarding the prioritisation of delay-tolerant and

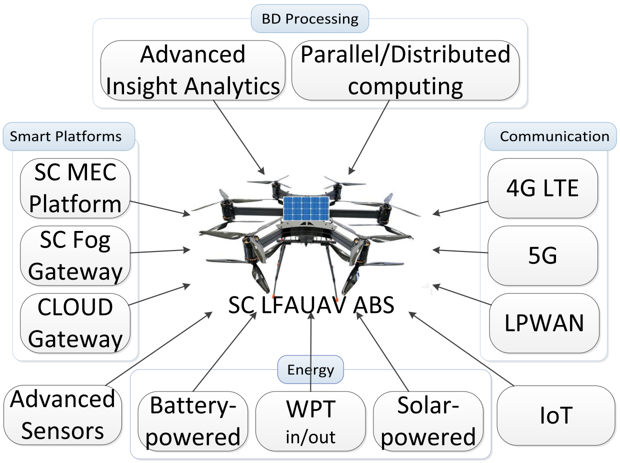

FIGURE 2. **Main features of LFAUAVs: Unification of EH and WPT, multiple communication technologies and advanced sensors along with high computing power and AIA.**

low-latency requirements by supporting resource-constraint nodes, mainly FAUAVs. The framework — FAUAVinSCF proposed in this study as a moderator that aims to integrate the components and abilities of SC and FAUAVs in a synergistic harmonised environment by taking the city dynamics into account with humanless technology is illustrated in Figs. 1, 2, 3, 4, 5, 6 and 7 in a multi-dimensional and multi-functional manner. With FAUAVinSCF, the communication, coordination and cooperation between FAUAVs and other SC components are provided using SC agents running on the SC LFAUAV MEC platform to meet the urgent input requirements of low-latency real-time decision-making by covering all concerning Region of Interest (RoI) beyond FAUAVs' perception to plan safe and optimal flights. First, the architecture of FAUAVinSCF is explained in Sections III-B1, III-B2, and III-B3 before exploring its virtues in Sections III-B4, III-B5, III-B6, III-B7, and III-B8.

1) FAUAV INFRASTRUCTURE DESIGN WITHIN SC

Due to the limitation of payloads, it is infeasible to carry sophisticated heavy sensors, which will lead to increase the power consumption and drastically decrease the flight time [96]. Moreover, due to the limited power available onboard, UAVs must make careful decisions about how to best utilize power for communication [97] and processing where the communications requirements [71] and data processing consume much energy. The problem deteriorates if UAV swarms experience poor network connectivity [95]. Different from conventional terrestrial communication channels that usually suffer from more severe attenuation over distance, shadowing and fading due to multi-path scattering, the A2G communication channels are typically LoS-dominant due to the higher altitude of UAVs leading to the establishment of robust communication links, especially in rural and suburban environments [24], [98], [99]. Effective multi-UAV coordination and UAV swarm operations need to be designed for ensuring reliable network connectivity [100] and energy-aware UAV deployment and operation mechanisms are needed for intelligent energy usage and replenishment [72]. Each FAUAV agent can avoid colliding with other agents, allowing for safer mobilization of the swarm agents while enabling effective implementations of the swarm operations that are resilient to the addition or loss of agents. Lost agents do not threaten the overall swarm behaviour because of the minimal knowledge each agent holds and this motivates the incorporation of swarm technology into the SC infrastructures [101]. Within this context, a FAUAV-SC network architecture as illustrated in Fig 3, is proposed in this study to deliver the required efficiency, availability, reliability, versatility, and scalability for fostering an orchestrated harmonised FAUAV-SC collaboration by maintaining end-to-end desired communication latencies within milliseconds.

With the proposed FAUAV-SC architecture (Fig 3), the appropriate geographic deployment of LFAUAVs close to end-nodes (i.e., other resource-constrained FAUAVs, SC components, mobile users) is executed by both covering all UAV aerial space and city ground areas. The FAUAV aerial traffic integrated with SC is orchestrated with the city UTM system to provide a thorough FAUAV swarm optimization leading to smarter cities. In this architecture, most of the jobs requiring extensive processing and computing, in particular, on FAUAVs are offloaded to the SC LFAUAV MEC platform for quick and thorough processing, which will help resource-constrained FAUAVs to save their battery power to realise their missions efficiently. LFAUAVs as connected devices establish multiple heterogeneous communication links based on A2G, A2A, and A2U enabling more ends to be served on a multi-purpose manner and a wireless basis dynamically, rapidly and simultaneously. It may not be possible to cover all the aerial space with a limited number of SC LFAUAVs in hand regarding large city sizes. In this case, FAUAVs are expected to complete their missions without needing the help of LFAUAVs where no links are established with LFAUAVs. Technically speaking, due to any probable connection failure with LFAUAVs, FAUAVs equipped with cellular communication technology can use the many of cellular BSs already deployed citywide to connect SC applications again using high-data bandwidth or they with no cellular connection abilities can communicate through the satellite communication to contact with SC and complete their missions using low-data rate transmission as illustrated in Fig 3. This infrastructure will facilitate the incorporation of FAUAVs into the National Airspace System (NAS) as well, which will increase the secure use of citywide and nationwide aerial space. The proposed communication approaches that are the backbone of the proposed framework are elaborated in Section III-B2. The communication requirements between the smart platforms, namely, the SC MEC, edge, and fog platforms and cloud platform enabling wider synergistic orchestration of resources through citywide, nationwide and worldwide are revealed in Section III-B3.

LFAUAVs allocate their resources between FAUAVs along with the demands of SC applications based on delay-tolerant

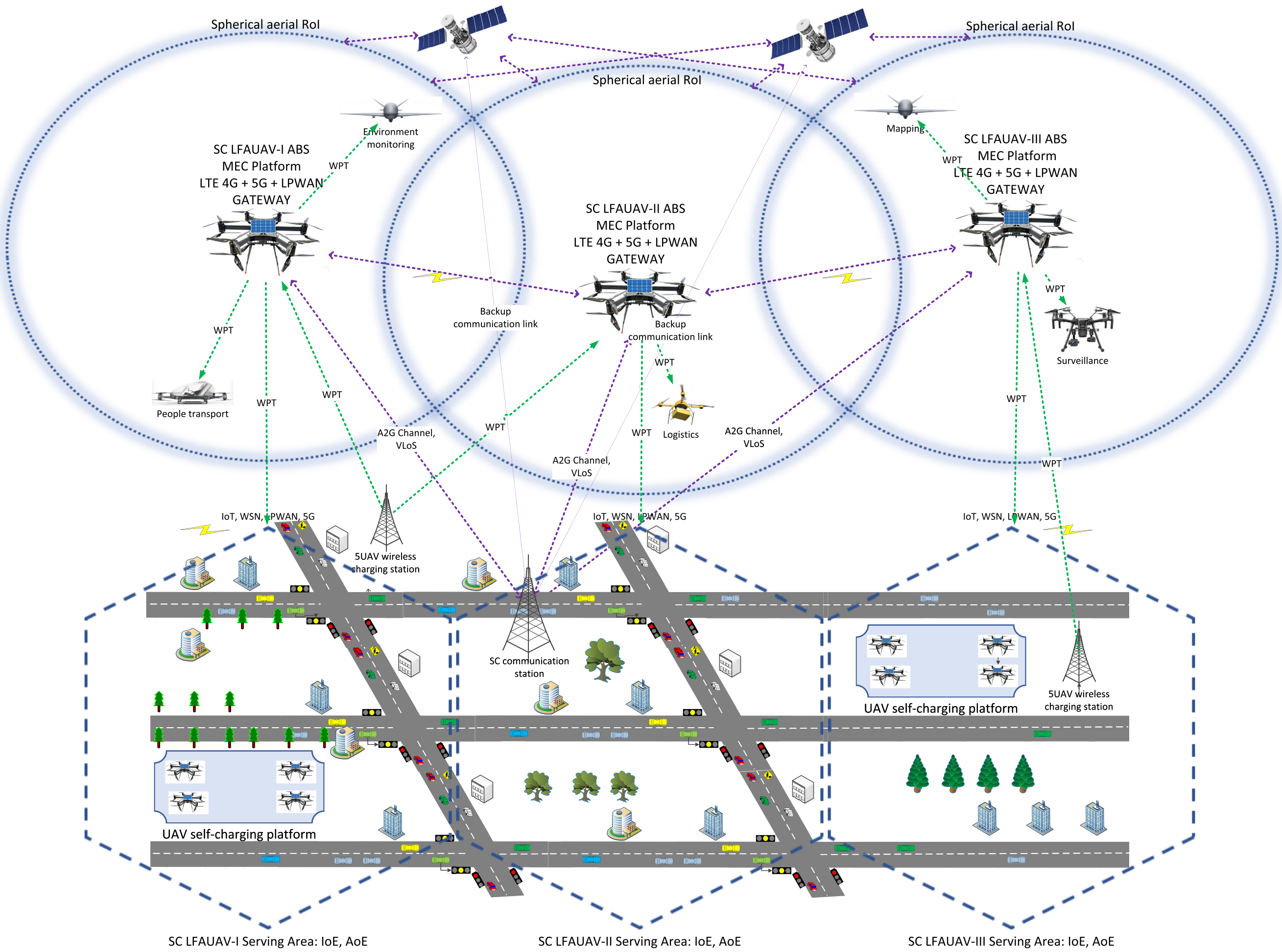

FIGURE 3. Integration of FAUAVs with SC. The blue spheres at the top correspond to the aerial UAV traffic control areas for each LFAUAV. The dashed blue beehive-shaped hexagons at the bottom indicate the wireless coverage areas of each LFAUAV assisting the existing communication infrastructure and the citywide coverage as shown in Fig. 6 with a beehive scheme.

and low-latency requirements. All LFAUAVs within the LFAUAV SC MEC platform are connected either via SC or direct connection with one another and each one is responsible for a specific spherical aerial space to coordinate the air traffic as presented in Fig 3. The communication traffic and management of the LFAUAV SC MEC platform is distributed among several LFAUAVs, which alleviates the congestion problem substantially with the nearby ultra-low latency communication services. The delegation of the management control of any FAUAV from the current LFAUAV to the other LFAUAV is ideally executed in the overlapping sections of the specific spherical aerial spaces controlled by these two LFAUAVs. With such citywide deployment of LFAUAVs equipped with advanced communication technologies to manage FAUAV aerial traffic, in turn, can be employed as a backbone to support highly available, high throughput and low latency communication links required by citizens and city businesses by covering large districts in urban areas with the help of the wide LOS capabilities, by which the mobility of city is expected to increase substantially. 3D modelling of the ground and aerial traffic involving city statics and dynamics is explored in Section III-B4. The routing approaches concerning ground and aerial requirements are explained in Section III-B5 using the beehive coverage scheme. The proposed approaches to support SC ground nodes using the LFAUAV SC MEC platform are presented in Section III-B7.

To make LFAUAVs and FAUAVs complete their mission efficiently, their batteries need to be recharged during their long-range flight on their way without any considerable delay. Nguyen *et al.* [32] propose the hybrid EH system, which can simultaneously harvest power from solar and RF energy sources for longer UAV flights. A project developed by Chen *et al.* [44] present an automatic and high-efficient wireless power transfer (WPT) using inductive coupling to supply UAVs with a distance of 12 cm where the voltage increases within closer ranges: A WPT kit can charge 3S 1500 mAh Li-Po battery with up to 1000 mAh automatically once UAVs are landed, without manual operation and 24V DC is supplied to the transmitting side of WPT with the operating frequency at 180kHz and once the battery is fully charged, the charging process also stops automatically. Design and implementation of a WGChS enabling UAVs to charge autonomously were carried out by Junaid *et al.* [102]. Similarly, in the proposal, the main constraint of LFAUAVs, the battery life is aimed to be extended using both light EH solar panels and aerial and ground WPT for prolonging the operational time significantly. Besides, LFAUAVs as a UAV-enabled WPT can be used for charging FAUAVs in the hovering position along with ground mobile nodes (e.g., IoT, sensor nodes) using LoS energy transmit links with UAV-mounted mobile energy transmitter as suggested by [48], [103], [104]. In this sense, charging of FAUAVs during their mission is carried out by LFAUAVs in the proposed architecture using A2A WPT via LoS within closer distances with reduced propagation loss and link degradation leading to faster recharging. LFAUAVs as a UAV-enabled WPT can carry an energy source and thus not consume its energy to transfer wireless energy and even UAVs with smaller sizes can do this job effectively [71]. Furthermore, LFAUAVs and other FAUAVs can be directed to the most appropriate autonomous WGChSs (i.e., UAV self-charging stations with both contact-based charging and WPT charging abilities in Fig.3) to recharge themselves in an autonomous manner whenever they need to complete their missions within longer ranges than their maximum travel distances. The ground WPT stations are distributed around the city optimally as shown in Fig 3. LFAUAVs on duty are swapped with the support LFAUAVs whenever they need to leave their positions either for charging or maintenance. The most up-to-date data along with all duties are transported to the replacing LFAUAV without any interruption of the services or handover failures using VMs and effective protocols. It is noteworthy that the high level of energy consumption of LFAUAVs by propulsion, onboard IoTs, data processing/transferring and communication requirements can be compensated by the FAUAVinSCF framework using WPT architecture and EH mechanisms. This architecture addressing the energy bottleneck of FAUAVs and helping them achieve their goals in very long ranges is expected to boost the wide acceptance of the use of FAUAVs in numerous challenging tasks.

2) COMMUNICATION AND DATA SHARING APPROACHES

Off-the-shelf diverse communication technologies, standards and protocols used in both SC and FAUAVs are shown in Fig. 1 C and D respectively. There are no agreed-upon data sharing protocols and standards based on the essential policies of synergistic moulding of these two developing fields. Regarding the recent improvements on 5G technology, it can be safely concluded that the emerging communication infrastructure — 5G/5GB with high data transmission rates will be the key enabler to provide not only seamless communication, but also low-latency abilities between SC and FAUAVs. LFAUAVs as SC aerial BSs (ABSs) and system orchestrators are the main blocks in the FAUAV-SC infrastructure to manage the A2A and A2G point-to-point and point-to-multipoint FAUAV communication traffic along with serving as the SC MEC platform.

Rapid and flexible deployment capabilities of LFAUAVs with a higher chance of the visual LOS (VLoS) links to FAUAVs and ground nodes (e.g., WSN, IoT, users) within SC due to their airborne nature and lower signal attenuation is the backbone in the establishment of an effective communication network between the SC components and low altitude/high altitude FAUAVs, which helps the synergic integration of these two rapidly developing fields. LFAUAVs with mounted communications infrastructure within the FAUAVinSCF framework are the responsible for the data traffic in specific overlapping aerial spherical RoIs over the city and related ground RoIs in the city aiming to cover the whole city data and communication traffic as illustrated in Fig 3. In a broader perspective, optimally distributed rotary-wing LFAUAVs as aerial central control facilities hovering in pre-specified static geodetic coordinate (latitude, longitude, altitude) points to achieve the maximum ground and aerial coverage in coordination with one another both manage the cooperative and collaborative FAUAV air traffic and assist ground communication links wherever needed, in particular, supporting coverage-constrained existing network infrastructures. The spherical aerial RoI for each LFAUAV is specified based on the biggest coverage areas possible, but reducing the signal attenuation and interference between FAUAVs and LFAUAVs to provide a high level of quality of services. Each FAUAV as an intelligent autonomous agent listens to the nearest LFAUAV and act accordingly with the directions given by the LFAUAV. Still, each FAUAV can make its own decision under any emergency conditions such as the link loss with LFAUAV or partial system failures detected by the onboard sensors. Most importantly, each FAUAV with their limited resources using the least energy consumption possible can communicate with other FAUAVs beyond their sensor and communication abilities via the established communication link with LFAUAVs as a point of control and management systems enabling integrated swarm sensing between FAUAVs, which generates a swarm intelligence easing the difficulties in the use of limited aerial space effectively, efficiently and safely. Communication and computation constraints of resource constraint FAUAVs are mitigated in this design by offloading these tasks into LFAUAVs with advanced abilities.

The main task executed by LFAUAVs in coordination with one another and SC edge/fog platforms is to manage the autonomous swarm intelligence of the FAUAV data network in the aerial space over a broadband 5G and 4G LTE wireless network. In this way, cellular-connected FAUAVs can communicate one another via LoS and BLoS without relying on satellite communications with low-data rate transfer. Agreed-upon data sharing standards and protocols between FAUAVs and LFAUAVs are crucial for the proposed FAUAV-SC infrastructure concerning a robust and safe aerial collaboration and cooperation. The secondary task is to expand the SC ground network connection capacity to support bandwidth-intensive applications by which the communication resources are distributed among ground users robustly to provide them with latency-sensitive communication links. In addition to on-demand, cost-effective deployment, onboard communication, and the flexible system reconfiguration compared to ground BSs, UAVs, in particular, can support better communication links between air and ground terminals due to less signal blockage and shadowing effects [10], [105], [106]. In this regard, it is worth clarifying that LPWAN technologies achieve long-range and low power operations at the expense of low data rate (a few hundred to a few thousand bits/s) and higher latency (typically in orders of seconds or minutes) are considered for those use cases that are delay-tolerant, do not need high data rates, and typically require low power consumption and low cost [87]. LPWAN and current cellular communication technologies can not alone address all SC and FAUAV aspects even though they still meet the needs of many SC applications. Most of the time, connecting many IoT applications, sensor nodes and services within IoE/AoE paradigm using wireless communication is the only feasible solution in urban areas. With the established design enabling a fair distribution of resources, several clusters of IoT devices connected to SC LFAUAV ABSs alleviate the network traffic significantly, which may otherwise cause congestion on any single BS with a huge number of IoT devices and sensor nodes asking for connectivity at a time. Effective management of IoT devices and sensor nodes in WSN and crowdsourcing using these nodes within the proposed architecture are elaborated in Sections III-B7 and III-B8 respectively. It is worth mentioning that the control and non-payload communications (CNPC) links (i.e., command and control from GCS to UAVs, aircraft status report from UAVs to ground, sense-and-avoid information among UAVs) are still essential to ensure the safe operations of non-autonomous UAVs [72].

3) ORCHESTRATION OF SC LFAUAV MEC, EDGE/FOG AND CLOUD

Continuous BD exchange in ultra-low-latency between the SC LFAUAV MEC and edge/fog platforms and cloud platform via cloudlets is highly imperative to establish the FAUAVinSCF framework using advanced communication channels such as 5G via the SC infrastructure. With efficient use of the MEC on board, SC edge/fog platforms and the cloud platform, FAUAVs can plan and operate collaboratively not only locally, but also throughout the entire city, statewide and even nationwide based on the larger observation of all current and impending aerial traffic activities by taking imminent aerial traffic plans into consideration, which significantly enhances the efficiency of FAUAV and SC mobility and sustainability of cities in an optimal fashion by exploiting the near-real-time data-intensive processing abilities. More specifically, the current activities and future plans with imminent route planning based on no-fly zones involving the learned experiences such as information about the routes, and aerial traffic conditions can be conveyed to other FAUAVs with the automation of FAUAVs within SC, which is elaborated in Section III-B5. The data traffic should be reduced as much as possible using the local computing power to meet the low latency requirements. LFAUAVs can be used as a MEC platform by other computing and resource constraint FAUAVs for high computing and low-latency applications requiring BD transmission and processing where LFAUAVs can communicate with SC fog platform and edge devices and cloud platform effectively using VMs as illustrated in Fig 4. Optimally distributed LFAUAVs within the SC LFAUAV MEC platform equipped with powerful onboard miniaturised computers can process a huge amount of data rapidly and the sharing of the processed information and insights as a service rather than all acquired sensor data (e.g., image/video, signal) reduces the data traffic significantly. LFAUAVs communicating with each other, generally on a VLoS basis with increased link performance and controlled by autonomous intelligent onboard AIA and efficient resource utilization mechanisms are clustered as distributed processing systems using VMs. Within this context, all the resources involving distributed databases and storage systems can be shared to increase the processing power enabling multi-task operations for low-latency, resource-hungry and data-hungry requirements. This design aims to reduce the chaos of sharing and processing a huge amount of data in a timely manner that may otherwise cause a massive channel load and congested network.

On the other hand, the processing of ground-wise or aerial-wise acquired BD processed at the SC edge/fog platforms with high computing power for decision-making and generating insight for specific FAUAVs diminishes the data traffic substantially as well. For instance, optimised routing schemes for FAUAVs to reach their destination based on their current locations can be determined within the SC edge or fog rather than sending all required BD to FAUAVs for their processing and route determination, which is explored in Section III-B6. Moreover, FAUAVs and SCs can leverage the benefits of the cloud for the execution of resource-hungry requirements such as long-term-sensor data storage for further processing e.g., health monitoring (prognosis/diagnosis of any imminent failure) or improvement of vehicle performance or execution of training algorithms requiring high processing power such as deep learning techniques. In this respect, context-aware data sharing standards and protocols should be agreed-upon between the stakeholders.

4) 3D MODELLING OF GROUND AND AERIAL TRAFFIC AND CITY STATICS AND DYNAMICS WITH FAUAVinSCF

Due to limited sensing capabilities, each autonomous vehicle has only partial information about the environment. The more knowledge about the broader environment, the safer and more optimal decision-making. In this sense, multiple LFAUAVs with advanced abilities and decentralised mode (Fig 2) integrated with SC are deployed to both perform collaborative semantic understanding of the ground and aerial statics and dynamics and help realise diverse multiagent tasks safely and optimally by reconstructing the 3D modelling of the city with geometric and semantic information.

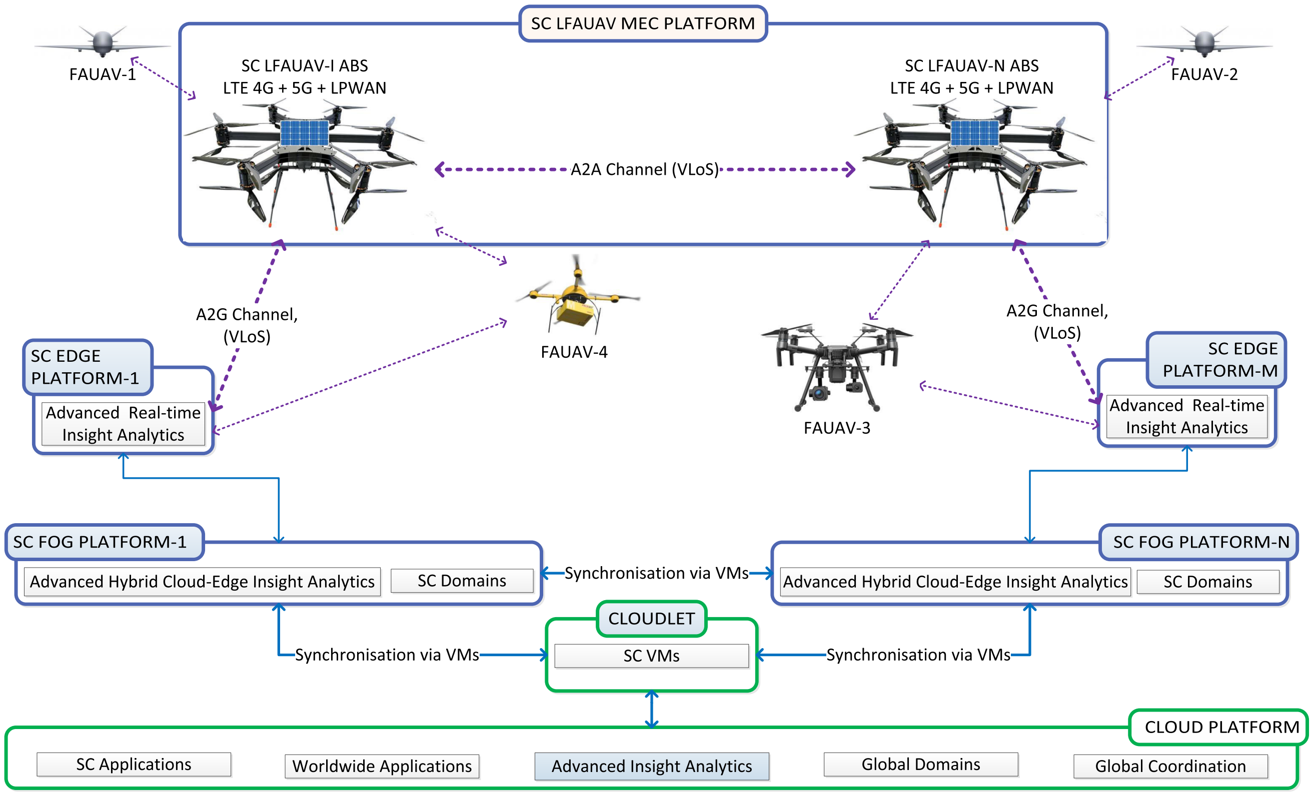

FIGURE 4. **Illustration of communication links between FAUAVs, SC LFAUAV MEC, SC edge/fog platforms and cloud platform to orchestrate the computing resources with scheduled tasks based on the latency requirements.**

Most of the vehicle manufacturers aim to deploy AGVs on city roads in 2021 [13]. In this sense, city road high-definition (HD) maps with lane-level accuracy are a topic of particular interest to both map providers and vehicle manufacturers [107]. Detailed static 3D HD maps for high-precision position down to a margin of error to 10 cm can be created today using real-time kinematic capabilities [108] and this is ten times as accurate as 2D maps that operate with a margin of error of up to a metre [109]. It is made possible with this 3D mapping to model road surfaces down to the number of lanes and their width, the curvature and slope of the road and surrounding signage [109]. To ensure the HD maps that AGVs use contain up-to-date information, HD maps should be refreshed weekly and generating and maintaining HD maps can cost millions of dollars per year for a midsize city [108] using the current approaches mentioned in [13]. Various companies, primarily Google have put huge investments into creating highly accurate HD maps [110]. A novel approach to generate the most up-to-date 3D city road maps was proposed by [13] using SC facilities and AGVs.

$$LFAUAV_a.3DAerialMap = LFAUAV_a.AerialData + \sum_{n=1}^{k} FAUAV_n(x, y, z).AerialData; \quad (1)$$

$$City_A.3DAerialMap = \sum_{n=1}^{t} LFAUAV_n.3DAerialMap; \quad (2)$$

$$City_A.3DGroundHDMap = City_A.3DStructureHDMap + \sum_{n=1}^{w} LFAUAV_n(RoI).GroundData; \quad (3)$$

$$City_A.3DMap = Eq.\ 2 + Eq.\ 3; \quad (4)$$

City 3D accurate up-to-date HD maps can be generated readily by the help of the sensor data acquired by LFAUAVs using their advanced sensors such as various cameras, lidar and radar in a cost-effective manner. The local maps generated by individual LFAUAVs are fused into a citywide map by the SC LFAUAV MEC and edge/fog platforms. In broader terms, 3D mapping of the terrain, buildings and other all city dynamics involving both mobile objects (e.g., vehicles, pedestrians) and static objects, in particular, the ones built recently (e.g., road structures) can be visually mapped by LFAUAVs using their advanced sensors (Fig. 1 E2) to help SC observe and manage both the ground and air traffic. The conceptual formulas to map the current 3D aerial traffic for the optimal and safe flight control with agile manoeuvring in the complex and dynamic urban environment are given in Eq. 1 for each LFAUAV aerial RoI by combining data acquired from heterogeneous onboard sensors of FAUAVs, and in Eq. 2 for the city — a combination of aerial RoIs of all LFAUAVs. The formula to map up-to-date ground HD city structures is given in Eq. 3. The 3D presentation of the city static structures and dynamics consisting of both aerial and ground aspects is given in Eq. 4.

$$City_A.3DRoadHDMap = City_A.3DRoadHDMap + \sum_{n=1}^{w} LFAUAV_n(RoI).RoadData; \quad (5)$$

Additionally, 3D HD dynamic road/street mapping obtained using LFAUAVs can be employed to enhance the already established 3D HD maps for city roads.[5] In this regard, the conceptual formula for observing the dynamic 3D HD city road map is shown in Eq. 5. These 3D modelling maps composed of semantic information can be exploited for various reasons, mainly by FAUAVs and AGVs to complete their missions with no accident using optimal routes through the city structures (e.g., optimally delivering a parcel to a house without hitting any obstacle in their paths). Furthermore, LFAUAVs integrated with AGVs via SC smart traffic applications can provide very useful real-time insights with VLOS abilities beyond the capabilities of AGVs' sensors to optimise their behaviours enabling increased mobility and safety on urban roads. In particular, AGVs can determine better routes for themselves to reach their destination using the instant traffic information provided by LFAUAVs readily, which leads to the sustainability of the city significantly.

5) AUTOMATION OF FAUAVs AND SC WITHIN FAUAVinSCF

Against the numerous improvements and approaches in FAUAVs and SC development initiatives, still, new approaches and techniques are required to cope with the non-linear environment effectively with an orchestrated use of resources leading to a better-automated cooperative ecosystem. LFAUAVs are mainly deployed to regulate the aerial FAUAV traffic and assist them to accomplish diverse missions optimally and safely integrated with all the SC components. With the proposed framework, not only can adjacent LFAUAVs communicate, but also, all LFAUAVs can communicate one another using parallel, distributed and coordinated resource allocation mechanisms within the SC LFAUAV MEC platform. Furthermore, all FAUAVs are connected to the SC LFAUAV MEC and fog platforms and from which connected to the cloud platform as explained in Section III-B3 (Fig 4) based on the SDN-based topology. In this way, all FAUAVs with different abilities can not only interact with each other through standard protocols with M2M communication links, but also, with SC components to exchange information and insights via this infrastructure enabling communication channels to FAUAVs to establish swarm intelligence applications with the concepts of IoD, IoE and AoE. FAUAVinSCF coordinates all FAUAVs' access to the airspace safely in an optimal manner. Moreover, FAUAVs can be directed to the nearest SC WGChSs or charged by

[5] Interested readers are referred to the study [13] for detailed information about the layers of the HD maps involving the approaches to obtain them.

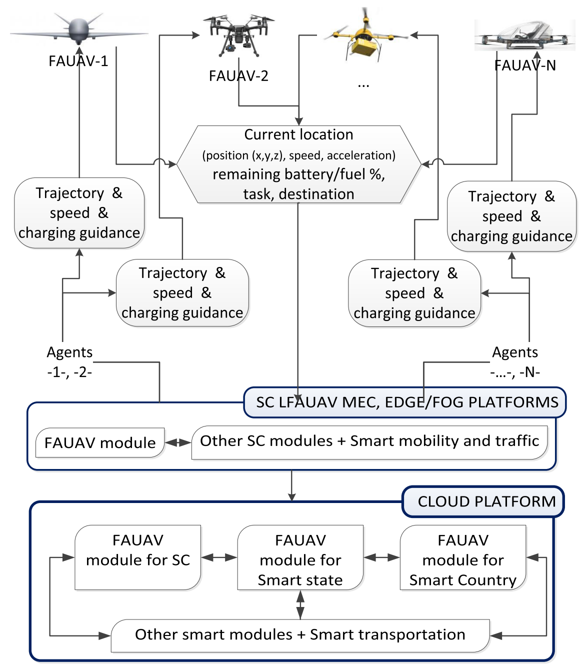

FIGURE 5. Dynamic route planning involving speed and charging guidance: An active agent per FAUAV is running in SC as illustrated in Algorithm 1.

LFAUAV WPT facilities as explained in Section III-B1 to complete their missions before their batteries deplete.

The interaction of FAUAVs with their surroundings in real-time with very small data transmission and communication delays enables better instant controlling and decision-making in a highly uncertain, unpredictable and volatile environment. Additionally, for better routing and decision-making, FAUAVs need a broader range of information beyond their sensor abilities, which requires a new communication channel and a new approach. The framework—FAUAVinSCF aims to orchestrate all the required resources by optimising the mobility through a near-real-time exchange of the dynamic information among FAUAVs. Safe and optimal routing of FAUAVs in urban areas with high building density is the key enabler for both proper automation and the robust integration of this rapidly developing technology with the other developing field — SC and therefore, special attention to this subject using the framework — FAUAVinSCF is paid in Section III-B6.

6) FAUAV ROUTING WITH FAUAVinSCF FRAMEWORK

Planning UAV flight paths or trajectories is the chief problem in autonomous UAV deployment within partially known dynamic environments [21]. Finding an optimal flying free of obstacles trajectory for a drone is a challenging task due to practical constraints such as availability of the air corridors, connectivity, battery limitation, collision, and terrain avoidance [94]. UAVs are usually expected to follow pre-determined fixed direct routes. However, the path yielding to the shortest distance is neither an optimal nor a safe option where the status of the aerial traffic changes drastically with increasing air traffic. Furthermore, FAUAV tasks may need to change during the mission or reserved flying zones may be updated based on city dynamic (e.g., bird migration routes, wind speed/direction), which requires the alteration of routes, sometimes slightly, sometimes considerably — even the mission may be cancelled. Many drone applications can benefit from a unified framework that coordinates their access to the airspace and helps them navigate to the points of interest where they have to perform a task [111]. Any architecture poised to provide this service must be scalable and be able to provide it to thousands of drones, which will share the congested and limited urban airspace [111]. It is a high priority to deploy FAUAVs in optimised routes by taking the non-autonomous UAVs and manned vehicles into consideration involving the city structures, facilities and weather conditions to accomplish coordinated and cooperative missions safely.

Appropriate real-time path planning that reduces the communication distances between LFAUAVs and FAUAVs for high-capacity communication performance based on their destination and constraints (battery-constraints, coverage-constraints and resource-constraints) along with the environmental constraints is crucial for safe and optimal planning. With this in mind, in the proposed approach, LFAUAVs and FAUAVs exchange instant dynamic information via a direct communication link as illustrated in Fig. 5. The optimal and collision-free navigation/path planning coordinated by the SC MEC/edge/fog computing platforms is carried out based on the positions, velocities and trajectories of all FAUAVs with generated imminent traffic maps in a 3D coordinate system concerning any impending particular time. The SC LFAUAV MEC platform in parallel and distributed processing and computing scheme knows the locations of other SC facilities (e.g., WGChSs) involving the city structures and accordingly can specify the appropriate trajectories with well-mapped aerial traffic as explained in Section III-B4 and FAUAVs are directed properly to accomplish their missions using these dynamic accommodated routes.

The broader SC agent-based dynamic route planning of FAUAVs is shown in Algorithm 1 using Eq. 4, in particular, Eq. 2 for the dynamic 3D aerial traffic mapping and Eq. 3 for ground-based missions. An agent per FAUAV runs on the SC LFAUAV MEC platform and it mainly determines i) LFAUAV RoI-based route planning through several numbers of RoI waypoints, ii) FAUAV trajectory within a specific RoI, iii) FAUAV direction to its particular targeted geodetic coordinate points (latitude, longitude, altitude) within the last RoI in the route, and finally iv) the route backward to the BS using the same concept mentioned in i, ii, iii. Instant aerial trajectory per FAUAV within particular RoIs is specified with the ideal 3D state vectors involving velocity. FAUAVs update their particular agents when the current destination changes and these agents propose modified optimised and safe routes instantly. Directing of FAUAVs to their destination is of crucial importance especially during their operation at low altitudes in a dynamic environment where

Algorithm 1: FAUAV Dynamic Route/Trajectory Planning Within the SC LFAUAV MEC Platform Using an Active Particular Agent per FAUAV.

```
Data: System input: AgentID & FAUAVID & FAUAVFeatures(MaxTravelDist,
      MaxPayload, MaxSpeed, ProcessPower, CommunicationAbility,
      ChargingType)& FAUAVTaskType &FAUAVStartLocation &
      FAUAVDefaultDestination & StartTime & CityHDBeeHiveMap &
      CityLFAUAVAerialMap
Data: Instant input:City_A.3DAerialMap (Eq. 2) & City_A.3DGroundHDMap
      (Eq. 3) & City_A.3DMap(Eq. 4) & FAUAVCurrentPayload &
      FAUAVCurrentLocation & FAUAVCurrentDestination &
      FAUAVSensedData & FAUAVFusedSensedData &
      FAUAVChangedDestination
Result: FAUAVRoute, FAUAVSpeed & FAUAVDestinationArrived &
        FAUAVChargingTime & FAUAVWPTChargingLocation (WGChS ||
        LFAUAVWPT)
=>FAUAV starts its navigation using its geo-info;
FAUAVCurrentLocation = FAUAVStartLocation (x,y,z);
FAUAVCurrentDestination = FAUAVDefaultDestination (x,y,z);
FAUAVCurrentRoILocation = FAUAVCurrentLocation.RoI;
FAUAVCurrentRoIDestination = FAUAVCurrentTargetLocation.RoI;
FAUAVSubmittedRoute = "";
while NOT FAUAVDestinationArrived do
    =>Check if the destination is changed during navigation;
    if FAUAVCurrentRoIDestination == FAUAVDefaultRoIDestination then
        =>Find the optimised route;
        RoI_current(x) = FAUAVCurrentLocation.RoI;
        RoI_end(y) = FAUAVCurrentDestination.RoI;
        =>Check if the last RoI reached;
        if RoI_current(x) != RoI_end(y) then
            [FAUAVRoute, FAUAVSpeed, FAUAVChargingTime,
              FAUAVWPTChargingLocation (WGChS || LFAUAVWPT)] =
              findOptimumRoute (FAUAVTaskType, FAUAVFeatures,
              City_A.3DAerialMap (Eq. 2), City_A.3DMap(Eq. 4), Eq. 6 <==
              (RoI_current(x), RoI_end(y)); sendNewRoute(FAUAVRoute,
              FAUAVSpeed, FAUAVChargingTime,
              FAUAVWPTChargingLocation);
        else
            =>Direction of the FAUAV to its specific point;
            diectFAUAV(FAUAVCurrentDestination.LFAUAV,
              FAUAVCurrentDestination (x,y,z), CityHDBeeHiveMap,
              City_A.3DAerialMap (Eq. 2) & City_A.3DGroundHDMap
              (Eq. 3));
        end
        if FAUAVSubmittedRoute == " " then
            FAUAVSubmittedRoute = FAUAVRoute;
            sendNewRoute(FAUAVSubmittedRoute);
        else
            =>Send the route if it is different;
            if FAUAVRoute != FAUAVSubmittedRoute then
                FAUAVSubmittedRoute = FAUAVRoute;
                sendNewRoute(FAUAVSubmittedRoute);
            else
                =>Direction of FAUAV to next RoI in FAUAVRoute;
                diectFAUAVNextRoI(FAUAVCurrentLocation.LFAUAV,
                  FAUAVSubmittedRoute.NextRoI,
                  City_A.3DAerialMap.CurrentRoI (Eq. 2));
                =>Wait for new input (next RoI, new destination);
                LISTEN; SLEEP;
            end
        end
    else
        =>Find the optimised route regarding new destination;
        FAUAVCurrentDestination = FAUAVChangedDestination(x,y,z);
        RoI_current(x) = FAUAVCurrentLocation.RoI;
        RoI_end(y) = FAUAVCurrentDestination.RoI;
        [FAUAVRoute, FAUAVSpeed, FAUAVChargingTime,
          FAUAVWPTChargingLocation (WGChS || LFAUAVWPT)] =
          findOptimumRoute (FAUAVTaskType, FAUAVFeatures,
          City_A.3DAerialMap (Eq. 2), City_A.3DMap(Eq. 4), Eq. 6 <==
          (RoI_current(x), RoI_end(y)); sendNewRoute(FAUAVRoute,
          FAUAVSpeed, FAUAVChargingTime,
          FAUAVWPTChargingLocation);
    end
end
```

many other FAUAVs are operating to achieve their missions. Each spherical RoI of LFAUAVs as displayed in Fig 3 has a number of pre-specified 3D collision-free UAV highways/paths and these paths are combined to establish

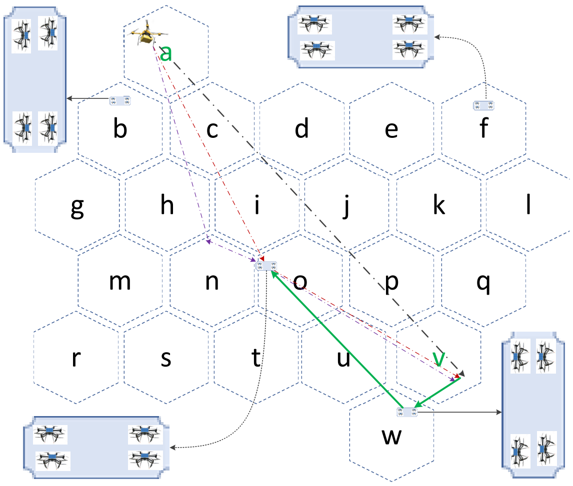

FIGURE 6. 3D expanded dynamic ground coverage of the city by LFAUAVs' RoIs presented in Fig 3 using the beehive scheme: Each component of the beehive represents one of RoIs of LFAUAVs such as "a" stands for RoI of $LFAUAV_a$ and "v" stands for RoI of $LFAUAV_v$ within the city, $City_A$.

routes/trajectories for FAUAVs to travel safely in an optimised manner. Each route can be used by multiple FAUAVs by adjusting the speed and distances as in the ground highways. These pre-specified routes are distributed among FAUAVs in an optimal manner based on their missions and destinations. FAUAVs broadcast their trajectory geodetic coordinates, their destinations, and their battery times left periodically to their agents. More importantly, LFAUAVs sense their RoIs using their advanced sensors such as LIDAR and RADAR to observe all the instant aerial traffic involving other non-autonomous UAVs as explored in Section III-B4 for a thorough optimal and safe decision making. Based on the interpretation of the instant sensed data, the particular agents guide FAUAVs to perform specific manoeuvrers safely such as moving to a new point, hovering, landing or changing their trajectories by coordinating their manoeuvrers with other FAUAVs in proximity to avoid any collision.

The determination of the FAUAV path by the SC LFAUAV MEC platform is executed using the beehive scheme as illustrated in Fig 6 based on the RoI-based route planning using the conceptual formula in Eq. 6 concerning i) the shortest possible route on the LFAUAV RoI waypoints, ii) aerial traffic, iii) constraints (i.e., battery-, coverage-, resource- and weather-constraints, the maximum number of FAUAVs allowed in a specific RoI_x ($RoI_x(max)$)), iv) SC facilities (e.g., WGChS, LFAUAV WPT), v) FAUAV features and v) characteristics of the task. Each component of this beehive represents one of RoIs of LFAUAVs where "a" stands for RoI of $LFAUAV_a$ and "v" stands for RoI of $LFAUAV_v$ within the city, $City_A$. The number of components in the beehive scheme change based on the coverage abilities of LFAUAVs and the size of the city. To make the route planning more understandable, the following algorithmic expressions are presented in plain English where a FAUAV in RoI_a at the point, $RoI_{a_{x,y,z}}$ managed by $LFAUAV_a$ is supposed to fly to the point $RoI_{v_{x,y,z}}$ managed by $LFAUAV_v$.

- Regarding the shortest possible route via the LFAUAV RoI waypoints: the route is determined with the waypoints through RoI_a, RoI_c, RoI_i, RoI_j, RoI_p, and RoI_v respectively as shown with the black dashed arrow and the same route backwards should be followed to reach its BS after completing its mission in RoI_v if there is no constraint (e.g., battery time (t_b) > flight time (t_f), the imminent number of UAVs in RoIs, namely, c, i, j and p is smaller than the maximum number allowed—$RoI_c(UAV_{num}) < RoI_c(UAV_{max})$, $RoI_i(UAV_{num}) < RoI_i(UAV_{max})$, $RoI_j(UAV_{num}) < RoI_j(UAV_{max})$, and $RoI_p(UAV_{num}) < RoI_p(UAV_{max})$).
- Regarding the battery constraint: the same route is determined where the FAUAV is tagged to be charged by one of LFAUAVs in the waypoints using the aerial LFAUAV WPT charging. The aerial charging may not be available concerning the dense aerial traffic — e.g., the large number of FAUAVs already tagged for this type of charging. In this case, the FAUAV is supposed to be directed to a suitable WGChS to be charged before its battery depletes. Accordingly, the route is determined with the waypoints through RoI_a, RoI_c, RoI_i, RoI_o, (RoI_p or RoI_u in terms of the less traffic, but prioritising RoI_u), and RoI_v respectively as shown with the red dashed arrow. The same route backwards is followed after accommodating recharging in RoI_w where the same circumstances apply, otherwise, the shortest route with the black dashed line is followed.
- Regarding the maximum number of FAUAVs in RoI_i ($RoI_i(UAV_{num}) > RoI_i(UAV_{max})$) along with battery constraint ($t_b < t_f$): Along with the same battery constraint mentioned above, there is a large number of FAUAVs already registered for RoI_i. In this case, the FAUAV is directed to a new route in which the battery charging service is provided and RoI_i is avoided. Accordingly, the route is determined with the waypoints through RoI_a, RoI_c, RoI_h, RoI_n, RoI_o, (RoI_p or RoI_u in terms of the less traffic, but again prioritising RoI_u), and RoI_v respectively as shown with the purple dashed arrow and the same way back after charging in RoI_w where the same circumstances apply, otherwise, the shortest route with black dashed line is followed.

7) MANAGEMENT OF WSN AND IoT WITHIN FAUAVinSCF

There has been growing research interest in applying UAVs for data collection and dissemination in WSN and ground IoT devices [112], [113]. The collaborative wireless network

$$Route_{(LFAUAV_{currentRoI(x)}=>LFAUAV_{endRoI(y)})}.AerialMap = \underset{LFAUAV_{currentRoI(x)}=>\ldots=>LFAUAV_{endRoI(y)}}{\arg\min} f(Time_{(LFAUAV_{currentRoI(x)}=>\ldots=>LFAUAV_{endRoI(y)})}).AerialMap; \quad (6)$$

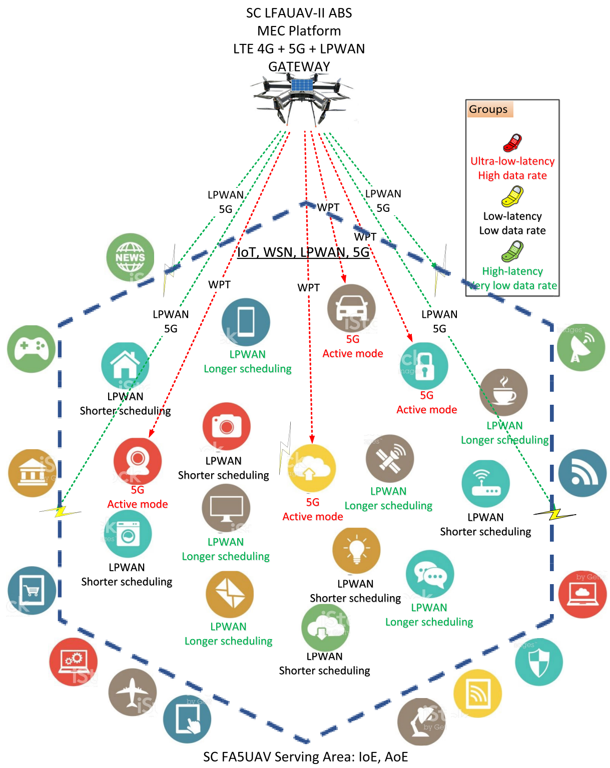

FIGURE 7. **Classification of wireless geographically highly distributed IoT, AMS devices and sensor nodes:.**

between UAVs and IoT devices plays a vital role in providing an efficient solution to the routing loop problem in traditional sensor networks, and enhancing the lifetime of the sensors through an optimal division of the load [51]. UASs can provide promising carriage facilities for data gathering in self-organized WSN topology by building up direct communication LOS links with sensor nodes. However, the speed of UAVs and network density are the main challenges [114]. To mitigate these challenges, in the proposed framework — FAUAVinSCF, the SC LFAUAV MEC platform composed of several advanced LFAUAVs equipped with 5G, 4G LTE, LPWAN communication technologies and high-level processing units is integrated with the SC edge/fog platforms and cloud platforms as illustrated in Fig 4. With a static hovering position, it serves as an air-based platform enabling a gateway between the smart platforms and SC distributed wireless nodes by covering the city network with the beehive scheme as displayed in Fig. 6 using several LFAUAVs where each component of the beehive represents one of the RoIs of LFAUAVs. One of the components of the beehive scheme managed by an LFAUAV is illustrated in Fig 7. Each LFAUAV is responsible for the pre-specified sensor nodes and IoT within its RoI. Technically speaking, LFAUAVs can act as gateways between sensors and a back-end SC data centres for delay-tolerant applications. Furthermore, SC LFAUAV MEC platform enabling time-critical communication between devices provides continuous wireless coverage and fuse BD leading to insights for other low-latency applications via M2M communication links.

Each sensor node within WSN has its sensed data in its memory and this data is supposed to be transmitted to the responsible LFAUAV and the memory is emptied after the transmission is completed successfully. The capabilities of sensor nodes are highly limited concerning the energy, memory, computing/processing and communication. Sensor nodes are in the sleep mode most of the time where one-bit transmissible input or radio duty-cycling can change their self-operating mode or data exchange mode via their activated/deactivated transceivers. This process is executed in coordination with BSs regarding the uplink and downlink data transfer operations by agreeing on sleep/wake-up schemes for reducing the energy consumption leading to increased battery lifetime. If the connectivity of the end-devices is supplemented with the LPWAN technologies in addition to the cellular or wireless LANs, operation of applications can be optimized by leveraging the benefits of each technology concerning the conflicting goals like energy efficiency, high throughput, ultra-low latency and wide-area coverage [87]. However, embedding all these communication technologies in a sensor node is highly expensive and not ergonomic. In this sense, in the proposed framework, devices in RoIs of LFAUAVs using one of these communication technologies are classified as high-latency, low-latency and ultra-low-latency. The listening schedule is adjusted for the first two groups with preferably LPWAN or 4G LTE as longer and shorter time intervals respectively as illustrated in Fig 7. For ultra-low latency nodes with 5G/5GB, on the other hand, the devices should be on active mode all the time. When high volume data transfer with very low time delay is required for bandwidth-hungry applications, 5G technology is employed to provide ultra-high data rate where LPWAN suffers the most concerning a very limited bandwidth. These types of architectural designs to meet the demands of the applications requiring ultra-low latency and high-data transfer rate with active mode decrease the battery life significantly, which is mitigated in the established architecture as elaborated below.

Despite promising capabilities, IoT networks suffer from limited device batteries and ever-evolving IoT services seek fully autonomous things without energy constraints [115]. To meet this demand, WPT technology is gaining increasing interest in 5G networks and IoT due to scarce energy resources and high-power consumption [116]. LFAUAVs with the wireless energy transferability can be deployed as WPT charging stations to charge the spatially distributed wireless battery-constrained IoT devices all over the city (Fig 7) where wired charging is not available before they are exhausted leading to the connection-lost. With this classification of devices regarding their communication requirements, the use of the LFAUAV WPT charging can be limited significantly for a reduced number of devices to prolong their network lifetimes. Serving to a reduced number of devices is of prime importance particularly with the laser transmitter where a single device can be charged at a time using the laser beams. Moreover, LPWAN technologies can still be used as a fall-back option for sending only low data rate critical traffic when cellular connectivity is not available [87] or not cost-effective. Furthermore, it is worth mentioning that Universal Mobile Telecommunications Service (UMTS) and LTE, were not designed to supply machine-type services to a massive number of devices [88] where cellular IoT (CIoT) architecture with 2G can support massive IoT traffic and with the proposed classification, the burden on current LTE communication channels is aimed to be relieved as well.

8) CROWDSOURCING WITH FAUAVinSCF

UAVs could potentially play a significant role in helping smart communities collect, analyse, process, and transmit the huge volumes of data generated by various IoT-based solutions in the smart ecosystem [14]. The study of the Internet of Vehicles (IoV) has sprung up, where vehicles act as sensor hubs to capture information by in-vehicle or smartphone sensors, then publish it for consumers [117]. Due to its ubiquitous usability, UAVs will play an important role in the IoT vision, and it may become the main key enabler of this vision [118]. The use of mobile crowdsourcing utilities such as UAVs equipped with IoT devices helps near-real-time monitoring of large urban regions effectively from a high-level view. A huge amount of information is already being collected within SC using highly distributed IoT, AMS, sensor nodes within WSN and highly distributed heterogeneous communication nodes as detailed in Sections III-A2 and III-B7. Following the development of IoV and crowdsourcing techniques, Vehicular Social Networks (VSN) as the emerging paradigm (i.e., the integration of IoV and social networks) are promising to solve the ever-increasing road accidents, traffic congestion, and other such issues that become obstacles to the realisation of the smart traffic in cities. VSN is likely to pave the way for sustainable development by promoting mobility efficiency [117] and human factors that impact vehicular connectivity using the cloud and conventional V2X communication frameworks.

The concepts of IoE and AoE mainly aim to combine many resource constraint highly distributed IoT devices and AMS intelligently in a worldwide network architecture for establishing larger smarter ecosystems. The interconnection of these systems in a highly synchronised ecosystem may suffer from communication bottlenecks mainly caused by the heterogeneous systems producing very BD in highly diverse formats. The SC LFAUAV MEC platform as the essential part of SC aims to mitigate these drawbacks by providing ultra-low-latency, ultra-reliable, and highly available two-way (A2G/G2A, downlink/uplink) advanced communication channels along with storage, processing and computing power using AIA to materialise the objectives of IoE and AoE. On the other hand, FAUAVs equipped with various IoT-enabled smart devices are contributing to the development of the IoT environment within these concepts. In other words, IoT-based devices mounted on FAUAVs can be used in the concept of Drone-as-a-Service (DaaS) and FAUAV Thing as IoT enabling continuous real-time monitoring, actuation and swarm intelligence with M2M communication services (e.g., regular real-time air pollution of specific areas, traffic information, weather information, crowd surveillance). Interested readers are referred to the study [51] for the various use cases of the smart UAVs equipped with advanced IoT abilities for improving the smartness of SCs. FAUAVs equipped with onboard sensors (e.g., CO_2 emission measurement sensors) as DaaS integrated with the SC LFAUAV MEC platform may turn into eyes, ears and noses of the city and can be requested by any customer to perform various real-time tasks, which reduces the aerial traffic by regulating the use of FAUAVs for the execution of several specific tasks where a FAUAV within a single operation can serve multiple demands at a time. Moreover, FAUAVs equipped with various IoT devices can be used for multi-purpose value-added services to collect specific types of environmental monitoring information (e.g., pollution measurement, weather reporting) while performing their primary missions such as the delivery of parcels. The insights as Insight as a Service (INSaaS) within IoE and AoE created by FAUAV Thing as IoT and SC nodes can be requested by any user. Cooperative crowdsourcing enables collaborative crowdsensing, which increases the efficacy of decision-making and the overall efficacy of SC significantly.

IV. DISCUSSION AND RESULTS

The challenges of urbanisation, if unmet urgently, would entail grave economic and environmental impacts [59]. Therefore, it is urgent to develop intelligent, autonomous, orchestrated and sustainable SC applications based on the specific city dynamics to address those challenges and improve urban daily lives. With this in mind, this study aims to bring the FAUAV promising technology into the heart of urban life. FAUAVs are safer to use due to their small size and they can fine-tune their positioning in 3D space in a manner that is unavailable to the larger aircraft [49]. FAUAVs should be perceived not only a transportation or logistics aspect but also an upheaval that amplifies the impacts on every part of people's life, strictly related to all the components of SC. As autonomous systems become more common in people's daily lives, they are expected to interact with each other, share information, and execute tasks collaboratively [119]. Therefore, FAUAVs cannot be treated as independent objects, but a part of their surroundings within SC involving the integration of human factors. To the best of the observed knowledge, this is the first comprehensive study both on the use of FAUAVs within SC effectively and on the integration of these two rapidly developing disciplines.

The acceptance of FAUAVs by most citizens lies in primarily successfully addressing the safety, security and privacy concerns along with alleviating the main constraints, namely limited battery capacities and payloads, limited computation and processing power and communication difficulties. In this respect, it looks like still there is a long way to go. The battery life has always been a big challenge for the use of UAVs efficiently and effectively regarding payloads and long travel requirements. Nowadays, some new kinds of batteries, such as fuel and solar batteries, have been invented to prolong the operational time by realising the long-lasting life of UAVs in the sky [80]. However, the flight altitude of UAVs affects the amount of harvested solar energy substantially [49] where the intensity of solar energy decreases with the decreasing light through clouds because of the reduced received solar energy flux at the solar panel [120]. Even though the flux problem with solar panels can be compensated with HAPs, most of the time LAPs are preferable and appropriate for most of the specific tasks and better communication links in urban areas. Furthermore, the use of WPT technology for charging UAV batteries seems a viable option to mitigate this constraint. The use of the EH mechanisms generated from ambient resources enables FAUAVs to fly much longer up to several months without landing. The other essential concern — processing power along with communication difficulties are being solved rapidly using advanced miniaturised avionics, state-of-the-art communication technologies, smart platforms and AIA techniques leading to a higher level of autonomy.

The arising problems related to particular city dynamics and autonomous UAS can be mitigated properly within a synergistic integration of SC and FAUAVs, which brings numerous benefits, primarily, i) transforming citizens' daily life into safer and more peaceful hormones functional environment with the most appropriate course of actions and ii) aiding socio-economic growth with multiple very useful applications with low-cost solutions. SC can help integrate all the dynamic options in a customised way empowered with mission/service-oriented cooperation using real-time insights by making timely decisions within the concepts of IoE and AoE. SC equipped with immersive communication technologies, powerful computing capabilities and smart MEC and fog platforms integrated with the cloud platform enables FAUAVs both to be connected to each other more effectively than ever and to use real-time and near-real-time insights for better decision-making. Low-latency, bandwidth-, data-, and resource-hungry network applications such as intelligent transportation systems (ITS) require an advance topology. Use of LFAUAVS as flying MEC platforms provides the required flexible topology for supporting those systems.

While low bit rates with LPWANs are unsatisfactory for various common data-hungry network applications, many SC and IoT services are expected to generate a completely different pattern of traffic, characterized by sporadic and intermittent transmissions of very small packets, typically on the order of a few hundred bytes, for monitoring and metering applications, remote switching/control of equipment, and many of these applications are rather tolerant to delays and packet losses, and hence are suitable for the connectivity service provided by LPWAN [88]. On the other hand, a huge amount of data volumes are generated by FAUAV onboard sensors along with data-hungry network applications and this very BD needs to be processed swiftly to support near-real-time decision-making, which requires effective collaboration between the SC LFAUAV MEC, fog platforms and the cloud platform. Recently, several approaches and techniques have been proposed to mitigate the difficulties in BD management, one of the most recent one is ''Management of geo-distributed intelligence: Deep Insight as a Service (DINSaaS) on Forged Cloud Platforms (FCP)'' [121]. With this approach, BD is processed with AIA tools and ready-to-use insights using high computing resources on the smart platforms are transported to be input into the other systems, which not only significantly reduces the data traffic, but also, decision-making abilities are accelerated. Furthermore, aggregated data in the SC fog platform and cloud platform acquired from the synergistic integration of FAUAVs and SC can be processed to increase the quality of services within the city. More obviously, many insights can be obtained from the huge amount of data and these insights can be useful in many aspects for many other fields, primarily, to transform the cities into more liveable places. Today's highly distributed and highly connected ubiquitous applications, primarily in SC require sustainable uninterrupted high data-rate communication services along with on-site resource-hungry data processing abilities and low-latency insight delivery mechanisms. In this context, an on-site SC LFAUAV MEC platform integrated with the SC fog/edge platforms and cloud platform for coordinating integrated FAUAV and SC applications is designed within the proposed framework — FAUAVinSCF.

Deploying fixed BSs in a timely and economical manner in temporary hotspots, disaster areas, complex terrains, and real-time locations of the users can be challenging [71]. To overcome these challenges, SC can benefit the use of LFAUAVs, especially where the expansion of conventional terrestrial infrastructure into every point of the city is neither cost-effective nor feasible. The LOS channel condition results in a higher data rate for ground-to-air transmissions compared with ground-to-ground transmissions [112]. In this regard, LFAUAVs as aerial mobile BSs complementing the existing terrestrial cellular communication infrastructure expand the terrestrial wireless communication networks and improve the performance and functionality of these heterogeneous cellular networks along with supporting other networks and sensor nodes within SC by providing fast, flexible, reliable and cost-effective coverage with LoS links where the number of small cells increase and wired or wireless communication is unavailable. In broader terms, LFAUAVs can be deployed as ABSs rapidly and swiftly providing internet access with onboard wireless transceivers for users, IoTs, WSN and LPWAN devices in overloaded cells or damaged or insufficient communication infrastructure or low-latency applications. Recently, extensive and intensive research has been conducted in determining the optimal placement of LFAUAVs as ABSs in Next Generation Cellular Networks for robust vertical (i.e., A2G) and horizontal (i.e., A2A) communication coverage concerning the aerial and ground communication traffic requirements and interference. The optimal ABS's altitude leading to maximum ground coverage and minimum required transmission power for a single UAV is implemented in [73], [122], the problem of providing maximum coverage for a certain geographical area using two UAVs is investigated in [122] and the efficient deployment of multiple UAVs is analysed in [103], [123], [124]. Effective LoS communication links with high availability, high data transmission rates, and low-latency abilities can be established by adjusting the locations of LFAUAVs. In other words, LFAUAVs equipped with appropriate 4G LTE, 5G and LPWAN technologies as proposed in this paper can be used to complement the existing communication infrastructure, particularly where the communication infrastructure is damaged after any disaster or where current infrastructure is not sufficient to support many link demands at a time on overloaded congested BSs, in particular, during big gatherings. Furthermore, LFAUAVs can collect data from many distributed wireless IoT and sensor nodes in WSN and disseminate the collected data into SC to be processed for delay-tolerant applications. Moreover, LFAUAVs can establish direct and fast communication links between IoT devices for ultra-low-latency information or insight requirements in supporting safety-critical applications such as Cooperative Intelligent Transportation System (C-ITS), flood detection, hurricane detection etc. Further studies that focus on incorporating the coverage of aerial traffic into ground coverage using optimally distributed LFAUAVs to manage as many as possible FAUAVs by mitigating 4G LTE and 5G communication interferences need to be carried out as an interesting and imperative research area. The results of the simulation study with various sceneries based on Algorithm 1 and Fig. 6 implemented in Matlab demonstrate that the constraints of FAUAVs can be mitigated significantly in urban areas and their use in realising a diverse range of missions can be optimised using the proposed methodology.

To summarise, the framework — FAUAVinSCF not only provides a well-designed flexible communication topology for the SC components, but also, enables more synergistic integration of these SC components involving FAUAVs within the concepts of IoE and AoE benefiting all the stakeholders. The benefits of using FAUAVinSCF may be numerous, i) effective management of city aerial traffic and mobility by not only knowing the current statuses of all FAUAVs, but also, projecting their future statuses using their planned routes, which leads to the mapping of imminent aerial traffic flow at any time with continuous aerial traffic planning, ii) providing SC insights, effective onboard AIA tools, and high processing and computing power to FAUAVs to process very BD for boosting their low-latency decision-making abilities, which reduces the payload burden on FAUAVs — e.g., less number of sensors, smaller and lighter avionics and computing and processing units, iii) support of the city IoT, WSN, LPWAN and citizens with low-latency and high-data-rate LoS wireless communication links as ABSs, and iv) providing effective EH mechanisms to FAUAVs, sensor nodes and IoT devices with autonomous wireless distributed battery charging stations and aerial WPT charging abilities.

FAUAVs as flying robots capable of immediately recognizing the change in a 3D environment, such as weather, radio wave, and magnetic field are defined by Kenzo [21] as drones that never crash and autonomously activate a safety device to prevent themselves from crashing such as using a redundant system, deploying a parachute or making a crash landing before crashing if an abnormality or an unplanned situation occurs. It is worth mentioning that perfect fully autonomous UAVs are not in the market yet. Nonetheless, there is no point to wait to make them perfect. They will never be perfect. Within effective FAUAV-SC frameworks — e.g., FAUAVinSCF, making FAUAV applications near-perfect can be possible, mainly making FAUAVs readily adopt and adapt their dynamic environments benefiting both the management of FAUAVs and sustainability and safety of SCs in multi-directional aspects. To conclude, there is a very good reason to unleash FAUAVs onto aerial city traffic if the abilities of them outperform those of human controllers along with the increased safety and security. Establishment of FAUAVinSCF framework requiring specialized SC facilities (e.g., LFAUAVs, LFAUAV WPT, WGChS) brings initial setup costs to the SC infrastructure along with continuous energy use, but, benefiting both the efficacy of FAUAVs and sustainability of SC in the longer period. The SC movement has been growing worldwide, but it will take another couple of decades for SCs to realise their game-changing potential [54]. Therefore, one of the main objectives of this paper is to make policymakers and city governors aware of that the changes related to FAUAVs and SCs are on their way and necessary planning to adopt these technologies and carrying out the necessary steps in their cities are urgent.

A. CHALLENGES

Essential challenges that need to be tackled before harnessing the benefits of the widespread use of FAUAVs incorporated into SC are provided as follows.

1) Readiness: The cities, politicians, policymakers, governors and legislators don't seem ready to embrace this forthcoming FAUAV technology right into the heart of the cities. There is plenty of room for controversy in the management of FAUAVs properly and ethically. All stakeholders within the public and private sector such as manufacturers, policymakers, governors, citizens should collaboratively work together to establish agreed-upon standards, protocols and regulations to catch up with the technology for incorporating FAUAVs into SC properly.

2) Communication: A big challenge for the establishment of smoother ultra-low-latency communication between the SC facilities and FAUAVs by avoiding channel congestion is optimally adjusting and synchronising the many communication/networking parameters both in SC and in FAUAVs (Fig. 1 C and D) within agreed-upon standards and protocols to match the goals of these two advanced application disciplines. Employing recent cellular communication technologies (e.g., 5G/5GB) to meet the needs of various use cases still requires comprehensive research to ensure desirable links. The emerging mmWave communications employed to achieve high-capacity UAV-UAV wireless backhaul could

lead to excessive Doppler shift [72] due to excessive mobility at both ends. New methods are required to alleviate this effect. In the proposed approach, static LFAUAVs in the hovering position reduce this effect significantly within an increased link quality. Furthermore, some of the varying communication standards in different locations such as the USA and Europe make it difficult for FAUAVs to communicate with each other and with the SC components, specifically, during their navigation between states and countries.

3) Reduction of interference: Due to the mobility of UAVs along with the lack of fixed backhual links and centralized control, interference coordination among the neighbouring cells with UAV-enabled ABSs is more challenging than in terrestrial cellular systems. Effective coverage of UAVs as ABSs concerning inter-UAV interference and beam-width was analysed in [103]. Effective trajectory coordination and cooperation between FAUAVs improves the aerial network performance leading to reduced interference [71]. Further effective interference management techniques specifically designed for UAV-aided cellular coverage are needed [72].

4) Denial-of-service attacks: Malicious interference may be readily originated from a radio transmitter located in the vicinity of communicating vehicles to cause denial-of-service [125], specifically, using a jammer with the reaction time in the order of tens microseconds, which can substantially increase the packet loss ratio at V2V links as demonstrated in the various experiments [126], [127]. Today's drone technology mainly relies on GPS services known to be easily spoofed or jammed [101]. New effective jamming avoidance techniques are required to retain the wireless services active at all time to avoid packet loss or packet transmission delay.

5) Cybersecurity and privacy: Cybersecurity is of crucial importance where the decision is made among various autonomous systems via M2M communication. Fake insights/inputs can be sent and FAUAVs should be well programmed to confirm the inputs using well-established authentication mechanisms. The other major concern of the use of FAUAVs integrated with SC with the effective and massive data collection abilities is the violation of privacy. Proper data usage mechanisms supported by appropriate laws should be enforced to discourage any violation attempt. An approach for privacy-preserving movements of UAVs in the urban environment for various tasks is proposed in [128].

6) UAV pollution and safety: Thousands of UAVs flying in the sky, following random paths, could be perceived as sky pollution that may impact the comfort of the citizens [118] along with highly increasing safety concerns. Therefore, good planning of UAV routes should also consider minimizing sky pollution leading to a safer environment.

7) FAUAV downtime: FAUAV charging using WPT technology should be as efficient as possible to minimise downtime and intensive research on this issue is already underway.

V. CONCLUSION AND FUTURE RESEARCH IDEAS

Emerging technologies on UAVs are evolving rapidly from the human-oriented to the machine-oriented concept with a high degree of autonomy. It is envisioned that the aspirations and investment in commercially available FAUAVs equipped with intelligent coordinated subsystems with human-like decision-making abilities will accelerate in an exponential rate in the following years, mainly with the perspectives of DaaS and UAV Thing as IoT within the concepts of IoE and AoE. The integration of FAUAVs with the SC ecosystem providing the citizens with an unprecedented ability to cope with the difficulties of living in a city is of crucial importance and transforming cities with FAUAVs still needs profound research from a philosophical, economical, behavioural and scientific point of view. From a commercial standpoint, FAUAVs with the cost-effective deployment without a human in the loop will benefit from the SC ecosystem to achieve their objectives and will be the key driver in developing new SC applications and the further improvement of the current SC ecosystem. To embrace this autonomy technology properly, to make the transformation from today's remote pilot-control to future's FAUAV smoother and truly to make it harmonious part of the cities with value-added services, new contemporary approaches and solutions that can turn the challenges of FAUAVs into advantageous and help design more sustainable and liveable cities with orchestrated synergistic integrations, optimised mobility, increased safety and security, and less footprint are needed. With this motivation in mind, this paper providing a discussion direction and inventive solutions for the challenges of FAUAVs has been developed to i) raise consciousness in this particular field, ii) create inspirational thinking, iii) help FAUAVs take their rightful and indispensable place with automated swarm intelligence in the schemes of recent SC development initiatives even though they still pose enough research challenges and last but not least, iv) transform the cities into smarter cities within the concepts of IoE and AoE. The proposed framework in this paper — FAUAVinSCF orchestrated by the SC ecosystem aims to make FAUAVs function efficiently as an essential part of SC via ultra-low-latency, ultra-reliable, and highly available advanced communication channels, which, in turn, will greatly enhance the SC services substantially.

Development of FAUAV approaches that can position swarm of FAUAVs in the aerial space safely and efficiently with fewer interferences based on their specific tasks will be a fruitful research direction. The virtues of the proposed framework are aimed to be demonstrated in a comprehensive simulation study.

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